In the name of Allah the Compassionate the Merciful

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Thermal Unit Commitment Problem for Khartoum North Power Station

A Thesis in Partial fulfillment of the Requirements for the Degree of M.Sc. in Electrical Engineering

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DEDICATION

TO

MY

FAMILY

MOTHER AISHA

WIFE HIBA

BROTHERS & SISTERS

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I would like to express my deep appreciation and thanks

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Abstract

This project aim to assign a priority order strategy (unit commitment schedule) of the steam and gas turbines at Khartoum North Power station (KNPS) according to the fuel consumption rates of each unit while considering some operational constraints.

In this study the unit commitment problem (UCP) and the solution methods used to solve it including the dynamic programming (DP) techniques were discussed, the Khartoum North Power Station structure including the eight units(4-steam units & 4- gas units) were presented and the necessary data to solve the unit commitment problem of the KNPS was collected .

The dynamic programming algorithm constructed to solve the unit commitment problem was transferred to a computer program using Visual Basic (VB) language and finally the VB program was run for 24-hour period with the data of the eight units of KNPS and a 24-period load pattern, finally an optimum unit commitment schedule was obtained according to the load pattern specified.

ملخص

يهدف هذا البحث الي ايجاد جدول اولويات لاختيار تشغيل وحدات توليد الطاقة بمحطة بحري الحرارية حسب معدل استهلاك الوقود لكل وحدة مع مراعاة بعض القيود التشغيلية.

في هذا البحث تم دراسة مشكلة جدولة الوحدات وطرق الحلول المتبعة مع التركيز علي طريقة البرمجة الديناميةة(حراكية) كذلك تم استعراض تركيبة محطة بحري الحرارية التي تحتوي علي اربعة وحدات بخارية واربعة وحدات غازية وتم جمع المعلومات المطلوب استخدامها في حل المشكلة .

تم تحويل الخوارزمية التي تم بناءها حسب طريقة البرمجة الدينامية لحل مشكلة الجدولة الي برنامج كمبيوتر بلغة البيسك المرئية وتم ادخال معلومات الوحدات الثمانية وادخال جدول حمولات ل24 فترة في البرنامج ثم تم اجراء تطبيق البرنامج وتم الحصول علي جدول تشغيل وحدات محطة بحري الحرارية الثمانية لمدة 24 ساعة حسب الحمولات المطلوبة.

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1 INTRODUCTION

1.1 Background

Like many systems that supply services to large populations, the electric power systems experiences cycles where the demand for electricity is higher during the daytime and early evening when industrial loads are high and lights are on and the demand is lower during late evening and early morning when most of the population are asleep.

Electric power systems also have a weekly cycle where the demand is lower over weekend days than weekdays.

This cyclical demand requires that electricity generation companies plan for generation of electric power on an hourly basis.

The problem of determining an optimum schedule of a set of generating units in a power system for a period of one day (24 hrs) or one week (168 hrs) that meet the demand load each period and minimizing the total operating cost while satisfying a set of operational constraints is known as unit commitment problem (note: to commit a generating unit is to turn it on) i.e the unit commitment refers to the strategic choice to be made in order to determine which of the available electric power generating units should be considered to be on line and supply the demand every period.

The unit commitment problem is one of economics, because to commit enough units and leaving them on line when they are not needed is quite expensive so a great amount of money can be saved by turning off the units that are not needed.

The objective of the standard unit commitment optimization problem is to minimize the sum of two cost terms:

1- The cost of power produced by a generating unit (the amount of fuel consumed).
2- The start up cost of a generating unit (prevailing temperature of boilers).

The unit commitment is suitable for power systems with wide variety of power plants (gas, coal, furnace, diesel, nuclear and etc) because for power systems with one type of power plants the power generating units have the same unit characteristics which will not influence the outcome.

1.2 The Objective of the Project

The project aims to assign a unit commitment strategy schedule for the steam and gas turbines of Khartoum North Power Station (KNPS) in Sudan.
A dynamic programming approach is used based on discrete data points pairing the fuel consumption with various output levels for each generator unit considering the capacity limits of the units, minimum up and down times and start up cost constraints.

1.3 Solution Methods

Many approaches to tackle the unit commitment problem have been developed, one of the most evident methods to solve the unit commitment problem (UCP) is the dynamic programming method (DP).
In this project the forward dynamic programming approach is used to solve the unit commitment problem (UCP) of Khartoum North Power Station (KNPS).
The dynamic programming algorithm developed for KNPS is transferred to a computer program using Visual Basic Language which provides a user graphical interface and allows reduction in the calculation time (32 bit compiler).

1.4 Thesis Layout

The topics of this thesis are organized in six chapters and an appendix contains the program code.
Chapter1 provides introduction to the unit commitment scheduling problem of power systems, the objective of this thesis, the method of solution applied and thesis layout.

Chapter2 provides a literature review of power systems economics, economic dispatch problem, hydrothermal coordination problem and the unit commitment problem covering in details the UCP formulation, operational constraints and the methods of solution.

Chapter3 provides an overview of SUDAN power system including historical background, existing thermal and hydro power stations, fuel resources for power generation and , existing transmission network and the daily load curve of the Sudan National Grid .

Chapter4 provides the theory of dynamic programming (DP) method of solution to the unit commitment problem including the DP algorithm and the necessary parameters for running the DP solution also this chapter shows the documentation to the Visual Basic computer program developed to run the DP algorithm.

Chapter5 provides the Khartoum North Power Station (KNPS) structure ,the data collected from KNPS, the application of the VB computer program developed to the unit commitment problem of KNPS and finally shows the result table of the optimum unit commitment schedule obtained.

Chapter6 discusses the conclusions to KNPS unit commitment problem and provides recommendations for future work..

The appendix contains the program codes arranged in four forms and a module.

2 UNIT COMMITMENT LITERATURE REVIEW

2.1 Economics of Power System

Recently, in electric power industry, the escalation in fuel prices around the world led the power generation utilities to spend more money in purchasing fuel for production of electric energy particularly as the demand increases. Therefore the efficient use of fuel is very important because any reduction in the amount of fuel consumed represent a significant reduction in the operating cost and also saving in the fuel resources because the natural resources of fuel are irreplaceable.

So the efficient and optimum economic operation of electric power generation systems takes important position in the industry of electric power systems which led the power generation utilities to compete to improve the operation efficiency of their power plants so a great deal of attention taken to solve the problems of the economical operation of electric power generation such as:

1- Economic dispatch of thermal units
2- Hydrothermal coordination problem
3- Unit commitment problem

2.2 Economic dispatch problem

For a set of electric generating units, the economic dispatch problem is to find the particular output levels for each available unit in the set that minimize the total fuel cost while meeting all of the load plus losses.

For a system that consists of n thermal units connected to a load P_{load}, where the input to each unit is F_i (cost rate of each unit).

The economic dispatch problem is to minimize the total cost F_T (sum of all units cost) for supplying the load P_{load} subject to a constraint that the sum of the generated powers P_i must equal the received load $P_{load.}$

That for the objective function:

$$F_T = F_1+F_2+F_3+\dots\dots\dots+F_n \qquad (1)$$

The constraint function is:

$$P = P_{load} \quad \textbf{(load)}$$

Or $$C = 0 = P_{load} - P \qquad (2)$$

Where : $P = P_1+P_2+P_3+\dots\dots\dots+P_n$

And

$$P_{i,min} \le P_i \le P_{i,max}$$

Where $P_{i,min}$ is the minimum output power unit i can offer

$P_{i,max}$ is the maximum output power unit i can offer

This is an optimization problem that can be solved by using advanced calculus methods that involve Lagrange function.

In order to establish the necessary conditions for an extreme value of the objective function we add the constraint function to the objective function after the constraint function has been multiplied by an undetermined multiplier (called Lagrange multiplier) say q and this equation:

$$L = F_T + q \cdot C$$

is known as Lagrange function.

The extreme values of the objective function results when we take the first derivative of the Lagrange function with respect to each of the independent variables and set the derivatives equal to zero.

For this case there are (n+1) variables, the n values of power outputs P_i plus the undetermined Lagrange multiplier q.

The derivative of the Lagrange function with respect to the undetermined multiplier q give back the constraint equation

$$C = 0 = P_{load} - P$$

While the partial derivative of the Lagrange function with respect to power output values P_i taken one at a time give a set of n equations shown:

$$dL/dPi = dFi/dPi - q = 0$$

or

$$dFi/dPi = q$$

which give the fact that for a minimum cost operating condition of the thermal power systems , the incremental cost rates of all units must be equal to some undetermined value, q .

Solving these n equations plus the constraint equation for the undetermined value q while satisfying the unit capacity inequalities, we determine the economic operating point.

In case the constraint equation include the network losses P_{loss} plus the load P_{load}, the economic dispatch problem will be more complicated to set up, however the constraint equation will be as shown:

$$\mathbf{P_{load} + P_{loss} - sum(P_i) = C = 0}$$

The same procedure is followed to establish the necessary condition for a minimum cost operating condition, by using Lagrange function and taking derivative of Lagrange function with respect to any one of the output power Pi result in the following n equations:

$$\mathbf{dF_i/dP_i + q\ .\ (dP_{loss}/dP_i) = q}$$

There are two general approaches in solving these n equations with the constraint equation to give the economic operating point:

The first is the loss-formula approach, in which a mathematical expression for the losses as a function of the power output of each of the units is developed.

The second is the optimal power flow approach, in which the power flow equations are incorporated as essential constraints in the formal establishment of the problem.

Then using the iterative process to solve for q, the undetermined multiplier giving the economic operating point.

Also there are many other methods in solving economic dispatch problem like:

1- LAMBDA- ITERATION
2- GRADIENT SEARCH
3- PIECEWISE LINEAR COST FUNCTION
4- DYNAMIC PROGRAMMING
5- BASE POINT AND PARTICIPATION FACTORS

2.3 Hydro-Thermal Coordination Problem

The objective of generation scheduling of hydro-thermal systems (GSHT) is to minimize the total operation cost of thermal units over the scheduling time because there is a general hypothesis that hydro units do not pose any cost constraints on the generation of electric power, as the source for generation of hydro power is the natural water resources.

In order to solve the (GSHT) problem for optimum operating point in such systems, firstly the problem is decomposed into thermal and hydro Sub-problems.

For thermal sub-problem, it is necessary to coordinate the area generations for reducing the operation cost without violating the transmission tie limits and satisfying the system reliability as conventional.

For hydro sub-problem, network flow are adopted to coordinate water usage over the entire time span (scheduling of water release) while satisfying the hydraulic constraints and meeting the load.

In dominantly thermal units power systems or for systems where there is a closer balance between hydro and thermal generation, hydro units are usually scheduled for peak load periods and generally considered as a replacement for the most expensive thermal unit as it can start up and shut down more efficiently i.e a given amount of water must be used to minimize the cost of running thermal units recognizing the hydraulic constraints that may exist.

For systems where most of the power generation is hydropower, the hydro units are considered as base load and the thermal units are economically scheduled for min. cost.

2.4 UNIT COMMITMENT PROBLEM

To commit an electric power generating unit is to turn it on, i.e bringing it up to speed and synchronize it to the system so it can deliver power to the network.

The unit commitment problem of thermal units is the problem of finding which units to commit every sub-period (1 hour, 2 hour,…) of a given planning period (1 day, 1 week,….) so that the customer demand (load) is supplied at minimum cost(optimal schedule) and satisfying a set of thermal operational constraints including capacity reserve , minimum up and down times , transmission flow limits , units output capacity limits.

2.4.1 UNIT COMMITMENT PROBLEM FORMULATION

As is true for many systems that supply services, an electric power systems experiences cycles, the demand for electricity is higher during the day time and early evening when industrial load are high and lights are on and lower during late evening and early morning when most of the electric equipments are off and population are asleep and also the electric power systems has a weekly cycle where the load is lower during the weekend days than the weekdays.

This cyclical demand means that not all units are needed all day which requires that electric power production companies plan for generation of power on an hourly basis for one day or one week

The problem is first to decide which of the available units is to turn on, and then to determine an economical dispatch schedule of the units for the whole period according to the sub-periods loads.

To determine an optimal economical dispatch schedule of a set of electric power generating units to meet a load demand while satisfying a set of operational constraints is called UNIT COMMITMENT PROBLEM(UCP).

Considering the real life operational constraints regarding each unit the UCP becomes more complicated.

The objective of the standard UCP is to minimize the sum of two cost terms:

Firstly: is the cost of power produced by generating units (the amount of fuel consumed).

Secondly: is the start up cost of generating units(prevailing temp. of boilers)

2.4.2 UCP CONSTRAINTS

Any individual power system impose different rules on scheduling of units depending on generation makeup and load curve characteristics so UCP involve many real life operational constraints like:

1- Capacity reserve

The total amount of power available at each hour must be greater than the load demand, the difference between the available power and the load is the reserve power, this reserve is used to prevent any far drop in system frequency (system disturbance) when a unit or more units are lost or unexpected increase in load occurs.

Capacity reserve include spinning reserve which is the reserve power from synchronized units, and off-line reserve which include quick-start diesel or gas turbines units as well as hydro-units and pump-storage hydro units.

Allocating capacity reserve requires that reserve must be a given percentage of forecasted peak demand or must be capable of making up the loss of the most heavily loaded unit and it must be allocated among fast-responding units and slow-responding units which allows the automatic generation control (AGC) to restore frequency and interchange quickly in case of unit failure, also reserve must be spread around the power system to avoid transmission system limitations to allow various parts to run as islands if they were electrically disconnected.

2- Thermal units constraints

Thermal unit can undergo only a gradual temperature changes which requires a time period to bring the unit on-line, as a result of such restriction in the operation of thermal power plant a various constraints arise like:

1- Minimum up time T_{up}

Once the unit is running it must be up for time T_{up} before it can be turned off (decommited). The minimum up time T_{up} arise from physical consideration associated with thermal stresses on the unit and are designed to prevent equipment fatique.

2- **Minimum down time T_d**

Once the unit is down (turn-off)it must stay down for a time T_d before it can be recommitted .The minimum down time T_d on the other hand are based on economical considerations and intended to prevent excessive maintenance and repair cost due to frequent unit cycling.

3- **Crew constraint**

For thermal plant consist of two or more units they can not both be turned at the same time since there are not enough crew members to attend both units while starting up.

4- **Start-up cost**

A certain amount of energy must be spend to bring the unit on-line which does not result in any MW generation from the unit, is known as start-up cost.

Start-up cost can vary from max. cold start value when a unit has been off for a long period, to a min. hot start value when the unit is recently turned off (boiler temp. still high)

There are two approaches to treat a thermal unit during its down period, in the first the unit boiler is cooled down and then heat back for scheduled turn-on. The second approach requires that sufficient energy be input to the boiler to maintain operating temp. which is called (banking). The cost for the two approaches can be compared so that the best approach cooling or banking can be chosen.

Formula for start-up cost when cooling

$$= \mathbf{C_c\,(1\text{-}e^{-t/r})\,.\,F + C_f}$$

where

C_c = cold start cost (MBtu)

F = Fuel cost

C_f = fixed cost (crew &maintenance)

r = thermal time constant for the unit

t = time the unit was cooled

start-up cost when banking

$= \mathbf{C_t \cdot t \cdot F + C_f}$

where

$\mathbf{C_t}$ = cost of maintaining unit at operating temp in MBtu/h.

Up to a certain numbers of hours the cost of banking will be less than the cost of cooling as shown in the graph of Fig.2.1 below.

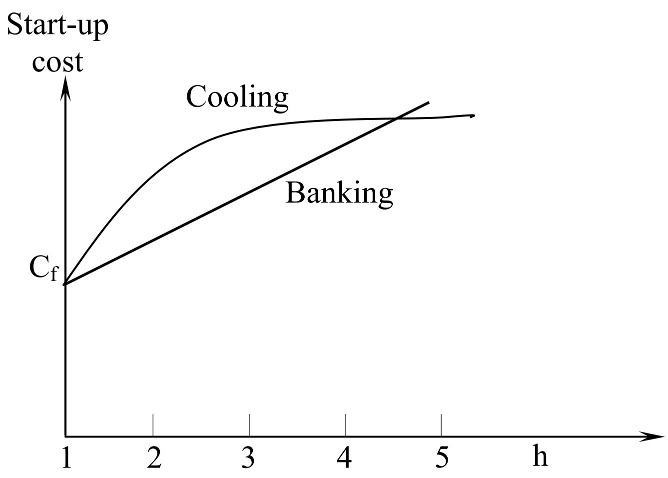


Fig. 2.1 : Time-dependent start-up costs.

5- **Capacity limits**

Any thermal unit due to physical limitation has min. output and max. output power, the min. output capacity of a unit is the minimum amount of MW the unit can offer where it is not possible to operate the generator at a level lower than this level and the max. output capacity of a unit is the max. amount of MW the unit can offer.

6- **Must - run**

Some units must be on line continuously because of voltage support on transmission lines or purposes of steam supply to other users (cogeneration plant), and also some units must run by nature like wind-turbines and large nuclear power stations.

7- **Fuel constraint**

For power systems that have limited fuel or that require to burn a specified amount of fuel in a given time, fuel presents a UCP constraint.

2.4.3 UCP Solution Methods

UCP is an economical optimization problem which when considering the real life operational constraints it becomes more complicated to solve.

One of the most evident methods to solve UCP is by enumeration (brute force) in which the cost of all possible combinations of power plants to supply the demand is examined (calculated).

Let us assume a system with :

1- n generating units to commit
2- Load pattern for M periods
3- The condition that for M loads and capacity limits on the n units are such that any one unit can supply the load and any combination of units can also supply the load.
4- The total number of combinations to be tested each period is:

$$\mathbf{C(n,1)+C(n,2)+C(n,3)+\ldots+C(n,n\text{-}1)+C(n,n)=2^n\text{-}1}$$

Where C(n,J) is the combination of n items taken J at a time.that is

$$\mathbf{C(n,J)= n! / (n\text{-}J)!\ .\ J!}$$

Where **J! = 1.2.3…….J** **J** factorial

For M load periods the max. number of combinations examined is equal to $\mathbf{(2^n - 1)^M}$

which becomes very large list of combinations to examine for plants with high number of units.

Fortunately, because of constraints on the units and other boundary conditions most of these combinations are left out the list where the most economical combinations are held.

This method give high dimensionality of possible solutions but it takes large time, therefore other methods have been devised for the solution of UCP, the most known are:

1- Priority-List Scheme

2- Dynamic Programming

3- Lagrange relaxation

2.4.3.1 Priority List Schemes

The priority list technique is the simplest method of UCP solutions. In this technique all units in the power system are ranked in a strict list (priority list) according to increasing full load average production cost of each unit, where the full load average production cost is simply the net heat rate at full load of the unit multiplied by the fuel cost.

Most priority list scheme are built around simple shut down algorithm that might operate as follows:

1-At each hour when load is dropping determine whether the shut down of the next unit on the priority list will leave sufficient generation to supply the load plus reserve requirements, if not continue operating the system as it, if yes go to the next step.

1- Determine the numbers of hours H before the unit will be needed again.
2- If H is less than the min. down time of the unit, keep the commitment as it, and g to the last step, if not go to the next step.
3- Calculate the production cost with the unit up for the next H hours. Then recalculate the cost when the unit is down for the same hours and adding the start up cost for either cooling or banking the unit whichever is less expensive.
   Compare the two costs when the unit is up and when the unit is down if there is sufficient saving from shutting down the unit, it should be shut down, otherwise keep it on.
4- Repeat this procedure for the next unit in the priority list and so forth.

2.4.3.2 Dynamic Programming Techniques (DP)

Dynamic programming is an approach developed to solve sequential or multi stage decision problems and also applicable for decision problems where sequential property is induced solely for computational convenience, so the word programming means to describe a set of rules which any one can follow to solve a problem where you need to find the best decision one after another.

In unit commitment problem, DP is used to trace an optimal schedule by an algorithms that running forward or running backward , but the forward approach has distinct advantage in solving UCP, because in forward approach the initial conditions are easily specified and computations can go forward in time as long as required. also the previous history of the unit can be computed at each stage.

For a power system which consists of n units the forward algorithm to compute unit commitment optimal schedule is shown in fig.2.2 below.

The formula to compute the minimum cost in hour K with combination I is as follows :

Fcost(K,I) = min.[Pcost(K,I)+ Scost(K-1,L:K,I) + Fcost(K-1,L)

Where

Fcost(K,I)= least total cost to arrive at state (K,I)

Pcost(K,I)= production cost for state (K,I)

Scost(K-1,L:K,I) = transition cost from state (K-1,L) to state (K,I)

Where State (K,I) is the Ith combination in hour K.

For forward DP two variables were introduced X & N where

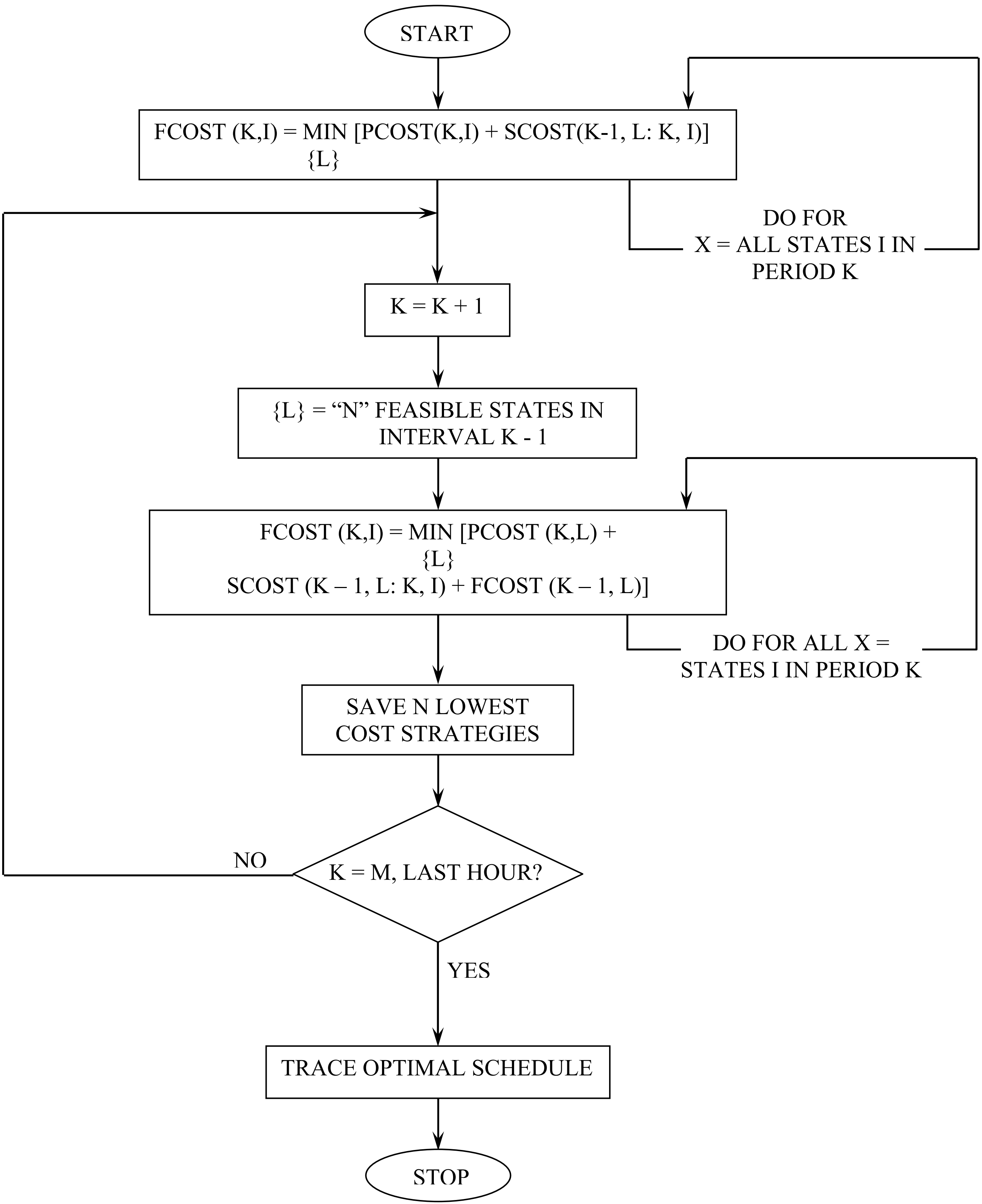
X= number of states to search each period

N = number of strategies or paths, to save in each step

A strategy is defined as transition or path from one state at a given hour to a state at the next hour.

These two variables X&N allow control of computational effort, where in complete enumeration the max. number of the value of X or N is ($2^n - 1$) where n is the number of units

while with simple priority list ordering the upper bound on X is n (the number of units),so reducing the number of N means that we discarding the highest cost schedules at each period and saving only the lowest N paths.



2.4.3.3 Lagrange Relaxation Solution

The Lagrange relaxation procedure solves the unit commitment problem by “relaxing’’ or temporarily ignoring the coupling constraints(loading constraints) and solving the problem as if they did not exist. This is done through the dual optimization procedure. The dual optimization procedure attempts to reach the constrained optimum by maximizing the lagrangian function with respect to lagrange multipliers, while minimizing with respect to the other variables in the problem

3 SUDAN : ELECTRIC POWER SYSTEM

3.1 HISTORICAL BACKGROUND

Electric Power generation in Sudan started early in 1908 when the first D.C diesel generator was installed in Burri area (east of Khartoum) with capacity of 100 KW and later increased to 500 KW.

In 1925 when the demand in Khartoum grow up, Sudan government (under British Administration) issued a company { EL NOUR COMPANY} to manage and develope the electric industry in Sudan to meet the growth in demand, so the generation units in Burri were replaced by larger ones with capacity of 3000 KW each.

In 1960 the Sudan national government issued the law of Central Administration of Electricity and Water (CEWA) to work under supervision of Ministry of Works which start to extend the electricity services to the big cities of Sudan.

In 1962 the first hydroelectric power station was installed in Sennar dam with a capacity of 15 MW followed in 1964 by Khasham Elgirba hydro power station (12.6 MW)and in 1971 by Roseires hydro power station which extended to(280 MW).

Also in 1962 the first transmission line 110 KV was installed to transmit power from Sennar to Khartoum followed in 1971 by the 220 KV transmission line between Roseires and Khartoum. In 1982 the law of National Electricity Corporation (NEC) was issued which took over management and development of electricity services in Sudan and since that time many developments in generation and transmission networks has been made.

3.2 EXISTING POWER SYSTEM

Recently a great development has occurred in generation and transmission systems of Sudan.

In the following we give a brief summary of existing generation plants, fuel resources and constraints and the structure of the existing transmission networks in both the National Grid and the isolated areas.

3.2.1 NATIONAL GRID EXISTING GENERATION PLANTS

In the National Grid the total available capacity in **2006** is around 800 MW of which about 60% thermal power and 40% hydro power distributed among the following power stations:

3.2.1.1 Thermal power stations:

1- Khartoum North power station

Located on Khartoum North 4 km away from the right bank of Blue Nile river.

The station Consist of 4-steam units fired on furnace (HFO- heavy fuel oil) and 4-gas turbine units fired on gas oil.

The steam units no.1&2 were installed in 1984 and rated at 33 MW for each unit with available capacity of 30 MW each unit, the steam units no.3&4 were installed in 1993 and rated at 60 MW each unit with available capacity of 50 MW each unit.

The gas turbines units no.1&2 were installed in 1992 and rated at 20 MW with available capacity of 17 MW each unit, the gas turbines units no. 3&4 were installed in 2001and rated at 25 MW with available capacity of 20 MW each unit.

2- Garri1 power station

Garri1 power station is a combined cycle gas turbines (CCGT) located at El Gaili about 70 km North Khartoum installed in 2003 .

The power station comprises four gas turbines (4X40 MW) and two steam units (2X30 MW),each two GT's are combined with one steam turbine making one combined cycle module fired on gas oil .the current available capacity of the station is about 164 MW.

3- Garri2 power station

Garri2 power station is an open cycle gas turbines fired on gas oil and located also at El Gaili near Garri1 .

The power station comprises three gas turbines units installed in 2003 with installed capacity of 40 MW and current available capacity of 28 MW each unit.The current available capacity of the station is about 84 MW.

4- Kuku Gas power station

Kuku power station is located on the eastern side of the Blue Nile river, the station comprises two gas turbines units installed in 1985, unit1 rated at 10 MW and unit2 rated at 14.4 MW with current available capacity of 9 MW for unit1 and 10 MW for unit2 .The station is fired by gas oil fuel.

5- El Fau diesel power station

Fau diesel power station located on El Fau (300 km south east Khartoum). The station consist of two diesel units installed in 2003 with installed capacity of 6.6 MW each unit and current available capacity of 5 MW each unit. The station is fired by furnace fuel (HFO).

6- Kassala diesel power station

Kassala power station (600 km east Khartoum) comprises eight diesel units

4X1 MW

1X3.7 MW

3X1.6 MW

with total installed capacity of 22.5 MW and current available capacity of 2.6 MW because there are six units out of service now. The station is fired by gas oil fuel.

7- Girba diesel power station

Girba power station is located at Khashm El Girba town (about 60 km south-west of Kassala) , the station comprises two diesel units:

unit1 installed in 1984 and rated at 2.9 MW while unit2 installed in 1990 and rated at 3.5 MW where the current available capacity of each unit is 2 MW. The station is fired by diesel oil fuel.

3.2.1.2 Hydro. power stations:

1- Roseires power station

Roseiries hydro power station located on the Blue Nile river about 500 km south of Khartoum is the largest power plant in Sudan it consist of seven units with total installed capacity of 280 MW and total available capacity of 276.5 MW. These units were installed between 1971 and 1989.

2- Sennar power station

Sennar hydro power station is also located on the Blue Nile river about 300 km south of Khartoum. The station was installed in 1962 and consist of two units each rated at 7.5 MW with current available capacity of 7 MW each unit.

3- Girba power station

Girba hydro power station located on Atbara river at Khasham El Girba town consist of

- Two units each rated at 4.12 MW together with four electric motors each 1900 hp which drive irrigation pumps.
- Three reversible axial flow pump\ turbines each rated at 2.07 MW in generating mode and 1.9 MW in the pumping mode.
- All these units were installed between 1961 and 1963.

4- Jebel Aulia power station

Jebel Aulia power station is located on the white nile river about 40 km south west of Khartoum. It consists of 80 hydro matrix turbines installed between 2003 and 2005 with total installed capacity of 28.8 MW.

3.2.2 Isolated Power Stations

There are many isolated power stations in Sudan scattered in towns that are not yet connected to the National Grid using local networks with distribution voltage levels of 33 kv & 11 kv , in the following we give a brief describtion of each of these power stations :

1- Port Sudan Power Stations

Located in Red Sea State and consist of two diesel power stations (B) &(C)

Station B : comprises six generating units fired on gas oil
2X0.775 MW with current capacity of 0.9 MW
2X0.6 MW with current capacity of 1.0 MW
2X1.4 MW with current capacity of 2.0 MW

Station C : comprises six generating units fired on diesel oil
3X6.2 MW with current capacity of 17.1 MW
3X2.3 MW with current capacity of 6.0 MW
the total available capacity in Port Sudan is 27 MW.

2- Karima Power Station

Located in Northern State, consist of :

2X2.3 MW units installed in 1999 with current capacity of 4.0 MW
2X2.2 MW units installed in 2000 with current capacity of 4.0 MW

The station is fired by diesel oil fuel with total installed capacity of 9 MW and total current available capacity of 8 MW.

3- Dongola Power Station

Located in Northern State, consist of :

2X0.6 MW units installed in 1996 with current capacity of 1.0 MW
1X1.1 MW unit installed in 1999 with current capacity of 1.0 MW
1X1.25 MW unit installed in 2001 with current capacity of 1.0 MW
2X1.0 MW units installed in 2002 with current capacity of 1.8 MW

The station is fired by gas oil fuel with total installed capacity of 5.55 MW and total current available capacity of 4.8 MW

3- Wadi Halfa Power Station

Located in Northern state, consist of three gas oil fired units:

3X0.6 MW installed between 1993/1997 with current capacity of 1.8 MW

4- El Dabba Power Station

Located in Northern state, consist of two diesel fired units :

2X3.0 MW units installed in 2006 with current capacity of 6.0 MW

5- El Obeid Power Station

Located in North Kordofan State, consist of :

2X3.4 MW units installed in 1997 with current capacity of 6.4 MW

1X2.7 MW unit installed in 1984 with current capacity of 1.8 MW

The station is fired by diesel oil fuel with total installed capacity of 9.5 MW and total current available capacity of 8.2 MW

6- Um Ruwaba Power Station

Located in North Kordofan State, consist of :

2X0.6 MW units installed in 1994 with current capacity of 1.0 MW

2X1.0 MW units installed in 2002 with current capacity of 1.8 MW

The station is fired by gas oil fuel with total installed capacity of 3.2 MW and total current available capacity of 2.8 MW.

7- Kadogli Power Station

Located in South Kordofan state, consist of :

2X1.0 MW units installed in 2004 with current capacity of 2.0 MW .

The station is fired by gas oil fuel.

8- Nyala Power Station

Located in South Darfur state, consist of :

2X3.5 MW units installed in 1986 with current capacity of 6.4 MW

2X1.2 MW units installed in 1986 with current capacity of 1.8 MW

The station is fired by diesel oil fuel with total installed capacity of 9.4 MW and total current available capacity of 8.2 MW

9- Ad Dein Power Station

Located in South Darfur State, consist of :

2X1.0 MW units installed in 2006 with current capacity of 2.0 MW

The station is fired by gas oil fuel.

10- EL Fasher Power Station

Located in North Darfur State, consist of :

3X1.6 MW units installed in 2006 with current capacity of 3.9 MW

2X1.2 MW units installed in 2000 with current capacity of 1.5 MW

2X1.0 MW units installed in 2000 with current capacity of 1.0 MW

The station is fired by gas oil fuel with total installed capacity of 9.2 MW and total current available capacity of 6.4 MW.

11- El Geneina Power Station

Located in West Darfur State, consist of :

2X0.4 MW units installed in 1994 with current capacity of 0.4 MW

1X0.3 MW units installed in 1989 with current capacity of 0.2 MW

2X1.0 MW units installed in 2002 with current capacity of 1.8 MW

The station is fired by gas oil fuel with total installed capacity of 3.1 MW and total current available capacity of 2.4 MW.

12- Juba Power Station

Located in Bahr El Jebel State, consist of :

3X1.0 MW units installed in 1985 with current capacity of 2.0 MW

2X1.0 MW units installed in 2002 with current capacity of 1.8 MW

The station is fired by gas oil and diesel oil fuels with total installed capacity of 5 MW and total current available capacity of 3.8 MW.

13- Waw Power Station

Located in Bahr El Gazal State, consist of :

2X0.8 MW units installed in 1983 with current capacity of 0.6 MW

2X1.0 MW units installed in 2002 with current capacity of 1.8 MW

The station is fired by gas oil and fuel with total installed capacity of 3.6 MW and total current available capacity of 2.4 MW.

14- Malakal Power Station

Located in Upper Nile State, consist of :

1X0.6 MW unit installed in 1995 with current capacity of 0.4 MW

2X1.0 MW units installed in 2002 with current capacity of 1.8 MW

The station is fired by gas oil fuel with total installed capacity of 2.6 MW and total current available capacity of 2.2 MW.

3.3 FUEL FOR POWER GENERATION IN SUDAN

3.3.1 Fuel Industry In Sudan

Since Sudan start production of petroleum oil in commercial basis in 1998 and build the oil export pipeline in 1999, a great change has occurred in the energy sector of Sudan, let Sudan to became an exporter of crude oil instead of importer and also became self sufficient in petroleum products after opening of Khartoum Oil Refinery in El Gaili in 2000.

Now, there are five oil refineries in Sudan as follows:

1- Khartoum refinery in El Gaili (70 km north of Khartoum) opened in 2000 with a capacity of 50,000 bbl/day and produces gas oil, gasoline and LPG .

2- El Obeid refinery opened in 1996 with a capacity of 15,000 bbl/day and produces furnace (HFO), gas oil, kerosene and naphtha.

3- Abu Gabra refinery located in South Darfor State opened in 1992 with small capacity of 2,000 bbl/day produces furnace(HFO) , gas oil and naftha.

4-Concorb refinery located in Khartoum (Shagra) opened in 1999 with capacity of 10,000 bbl/day.

5-Port Sudan refinery located in Red Sea State with capacity of 21,700 bbl/day (out of service since 1999) .

Generally gas oil represent about 50% of the total products of the refineries while furnace (HFO- heavy fuel oil) represent about 16% and gasoline represent about 15% .

3.3.2 Fuel For Power Generation In Sudan:

Sudan thermal power generation units burns three types of fuel namely:

1-Furnace (HFO- heavy fuel oil) , Sudan National Electricity Corporation (NEC) consumes more than 90% of the total production of HFO in generating electric power.

2- Gas oil , NEC consumes about 15% of the total product of the refineries.

3- Diesel oil (a blend of gas oil 70% and HFO 30%).

The main fuel constraints of power plants is the storage capacity and transportation while all power stations comprises storage tanks of different capacities that can operate the station for many days, the fuel is transported to the Sudan different power stations mainly by road tankers (90%)and railway tankers (10%) the only exception is the supply of gas oil to Khartoum North power station which delivered by pipeline from Kh. Refinery in Garry.

3.3.3 Fuel Prices:

The economic cost of fuel is derived from the international price of crude oil and oil products and then to be adjusted for the cost of delivering fuel to the power stations. The international prices of fuel fluctuate according to the political changes and crises across the world, for the last four years the oil prices rises from $30/bbl in 2002 to $70/bbl in 2006.

Fortunately because Sudan is producing oil , the prices of fuel delivered to the power stations is somehow stable for a relatively long period .

The prices of fuel delivered to power stations in 2006 according to NEC is as follows:

1- Furnace (HFO) 37,700 SDD/ton

2- Gas oil 122,350 SDD/ton

3.4 Existing Transmission Networks

The Sudan power system uses three voltage levels for transmission network in the National Grid namely 220 KV, 110 KV and 66 KV, while isolated area networks uses distribution voltages , 33 KV and 11 KV .

The existing transmission system in Sudan (National Grid) comprises:

1- 220 KV double circuit line run about 500 km from Roseires S/S (in Blue Nile State) to Khartoum State at KiloX S\S via Sennar S\S, Maringan S\S , Hasahesa S\S, Giad S\S then crossing the Blue Nile river at KiloX S\S in to Eid Babiker SS , Garri S\S and then to Shendi S\S and Atbara S\S(in River Nile State) about 300 km.

2- 110 KV line from Sennar S\S to KiloX S\S (in Khartoum) via sub-stations of Hag AbaAlla , Maringan, Hasahesa ,Giad and El Bagir .

   110 KV line from Maringan S/S to Gadaref S/S via Fau S/S.

   110 KV double circuit ring around Khartoum (about 70 km long) start at KiloX S/S via MagirusS/S , Ghaba S/S , Omderman S/S, Mahadia S/S, Ezergab S/S, Eid Babiker S/S, Khartoum North S/S, Kuku S/S back to KiloX S/S.

   110 KV double line from KiloX S/S to Faroug S/S (in the center of Khartoum).

3- 66 KV single line system in eastern state of Sudan from Girba to Kassala and from Girba to Gadaref where it is connected to the national grid via 110 KV line come from Maringan S/S via Fau S/S.

   All the 220 KV and some of the 110 KV substations were prepared with double busbar arrangement and step down transformers to step down the voltage for local distribution systems (33 kv&11 kv).

3.5 Sudan National Grid Load Curve

Like most power systems, the power system in Sudan follows a daily load cycle where the demand is higher during mid day and early evening when the industrial load are on and the loads of the commercial and governmental offices are high (air conditioning) and the domestic load is high(lights are on), and the demand is lower during the late evening and early morning when most of the load is off and population are asleep.

Also the power system in Sudan follows a weekly and annually cycles where the load is lower during the weekend days than the weekdays and lower during the cold season (winter) of the year than the hot season (summer).

A real daily load curves for two days are obtained from the load dispatch center of NEC and shown in Fig.3.5a&b below.

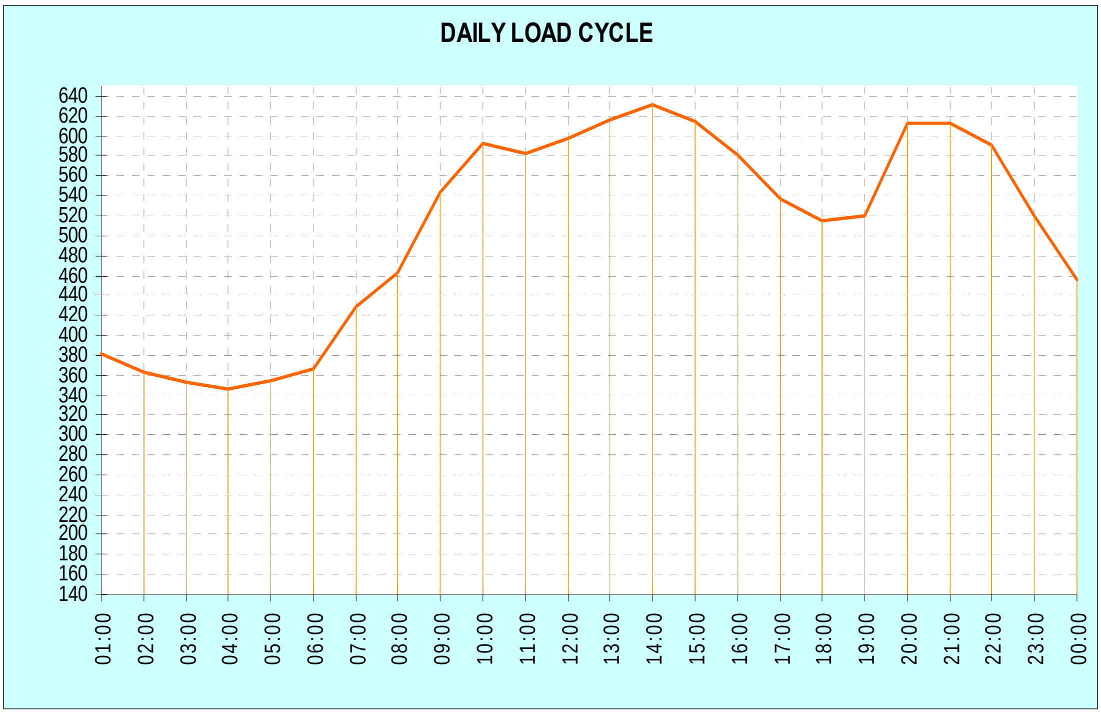


Fig. 3.5-a : Daily Load curve 15-April-06.

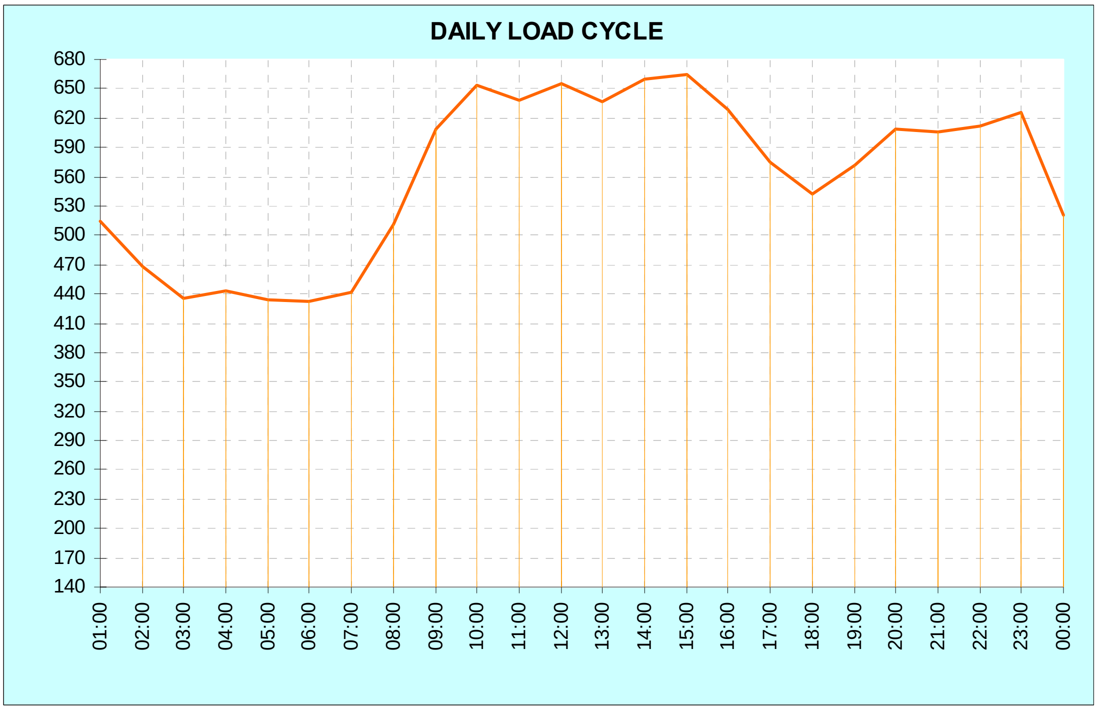


Fig. 3.5-b : Daily Load curve 17-October-06.

4 UNIT COMMITMENT SOLUTION PROGRAM

4.1 Dynamic Programming Method To Solve UCP

DP is a useful method in finding an optimal path from a number of possible paths while reducing computational efforts.

For a unit commitment problem (UCP) of electric power system which consist of a number of generating units, the dynamic programming (DP) is a very effective method in scheduling power generation by testing all feasible combinations of units (states) every time period (1 hour, 2 hours,… etc) for optimal state that supply the load for that period with minimum cost while meeting other operational constraints , feasible states are the unit combinations in which the committed units can supply the required load and meet the min. capacity each interval)

For reducing the dimensionality of UCP solution, instead of complete enumeration scheme, a strict priority list order according to full-load average cost of the units is combined with dynamic programming scheme reducing the computational efforts.

For DP approach the following assumptions are made;

1- A state consists of array of units with specified units on-line and the rest off-line.
2- The start up cost of a unit is independent of time the unit has been off-line (i.e it is a fixed amount)
3- There is no cost for shut down a unit.
4- A specified minimum amount of capacity must be operating in each period.

Starting from a previously determined optimal UC state and gradually adds power generating units to obtain optimal solution for higher demand is called forward DP, so DP algorithm can run forward from initial hour to the final hour of the scheduling period. Conversely DP can run backward starting from final hour back to the initial hour of the scheduling period.

4.1.1 Forward DP Algorithm

For a power system which consists of n generating units the forward DP algorithm to compute unit commitment optimal schedule is shown in fig. 4.1

The formula to compute the min. cost in hour K with combination I is as follows :

Fcost(K,I) = min.[Pcost(K,I)+ Scost(K-1,L:K,I) + Fcost(K-1,L)

Where

Fcost(K,I)= least total cost to arrive at state (K,I)

Pcost(K,I)= production cost for state (K,I)

Scost(K-1,L:K,I) = transition cost from state (K-1,L) to state (K,I)

State (K,I) is the I^{th} combination in hour K.

This is done for all states in {L} the feasible states of previous hour (K-1),used every period for calculation of transition costs from these feasible states of the previous hour(K-1) to the I^{th} state at hour K.

In forward DP approach a strategy is defined as transition or path from one state at a given hour to a state at the next hour.

Two variables X & N are introduced in unit commitment algorithm where:

X = number of states to search each period

N = number of strategies, or paths to save at each step.

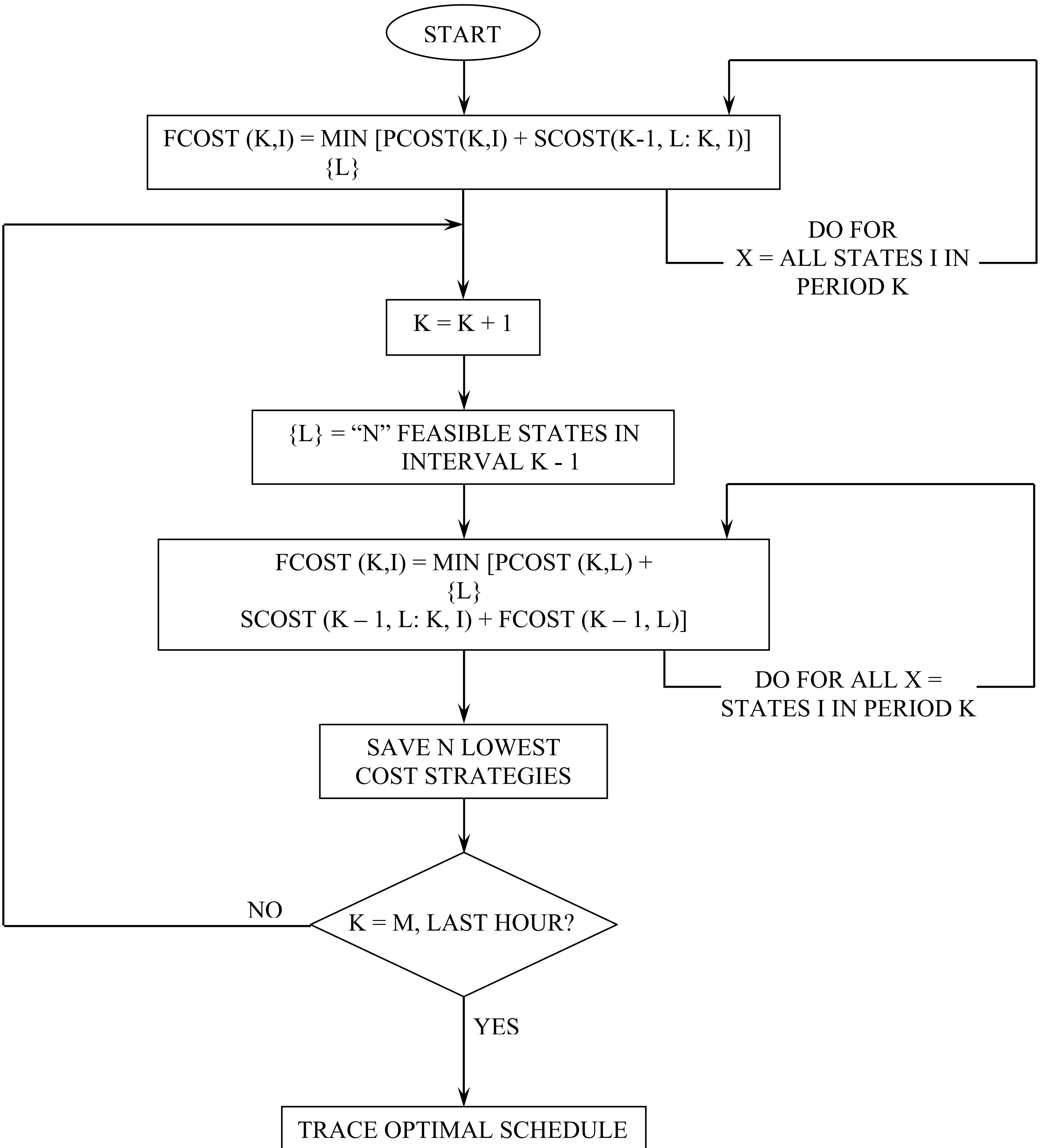
These two variables X& N allow control of computational effort.

A search path with N=3 and X=5 is shown in Figure 4.2

For complete enumeration approach DP the max. number of the value of X or N is ($2^n - 1$),where n is the number of units.

In simple priority list approach, the upper bound on X is n, number of units.

Reducing the number N means that we discarding the highest cost schedules at each period and saving only the lowest N paths.



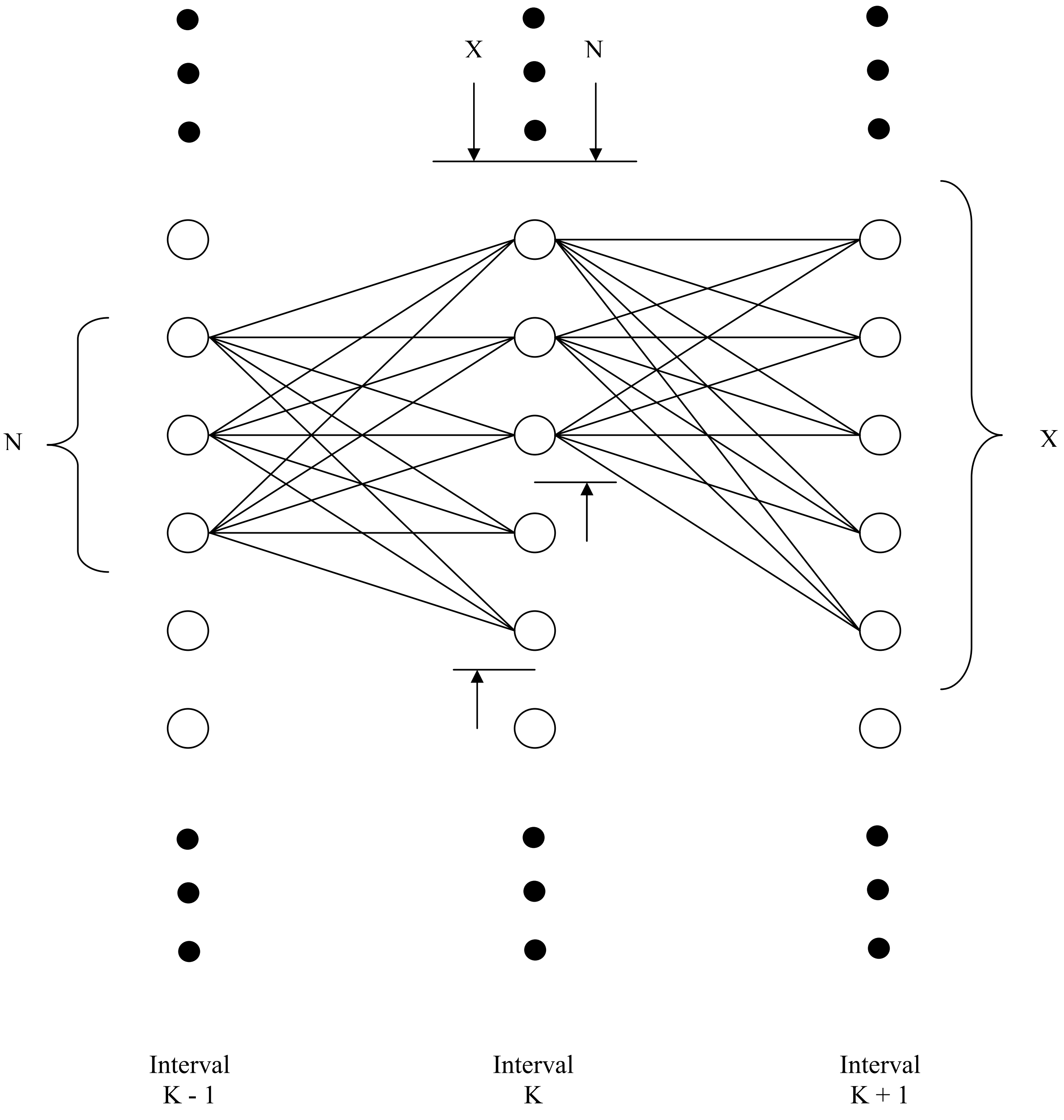


FIG. 4.2 DP algorithm with N = 3 and X = 5.

4.1.2 Power Generation Unit Characteristics

The unit characteristics is the input-output relation of thermal electric power generation unit where:

1-The input to the unit may be either:

In terms of heat energy H in millions of Btu per hour(MBtu/h),or in terms of tons of fuel per hour(ton/hour), or in terms of total operating cost rate(F) in dinars or dollars per hour.

2-The output of the unit is the electrical power output P to the electric utility system in MW.

Many different formats are used to represent input-output characteristics of a thermal unit, an idealized curve of the input-output characteristics is shown in figure 4.3 below.

Also an incremental heat rate characteristics for a thermal unit is introduced where the incremental heat rate characteristic is the slope (the derivative) of the input-output characteristics of the unit.

An incremental characteristics curve of idealized input output curve is shown in Figure 4.4 below:

For efficient computation in DP, a simplified model of the unit characteristics is used, where a linear curve with only a single step between minimum and maximum power points is used, in practical applications, two or three section-stepped incremental curves might be used as shown in Figure 4.5 below:

The operating cost rate function F(P) for the linear curve is:

F(P) = no-load cost + incremental cost . P

Where:

F is the operating cost rate of the unit in Dinar/hour or Dollar/hour

= H . fuel cost .

H is the heat input to the unit in Btu/hour or fuel consumption of the unit in tons/hour.

Fuel cost is the price of fuel in terms of Dinar/Ton or Dollar/Ton.

The incremental cost = incremental fuel consumption rate multiplied by fuel cost

dF/dP = dH/dP . fuel cost

Where for the simplified model of the unit characteristics

The incremental fuel consumption rate in (Ton/MWh) =

$$\frac{\textbf{Full load fuel consumption rate(Ton/h) - no load fuel consumption rate(Ton/h)}}{\textbf{Full load Power (MW)}}$$

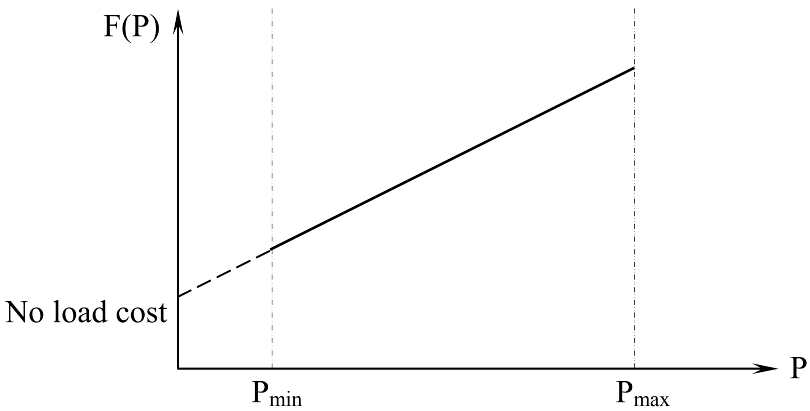


Fig. 4.3 : Input – Output Characteristics.

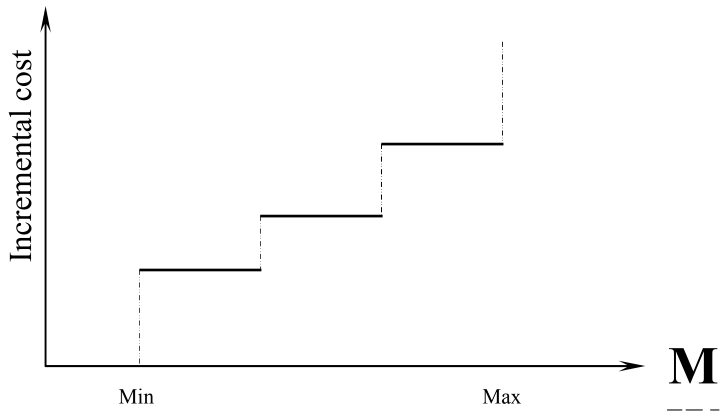


Fig. 4.5 : Three section-stepped incremental Characteristics.

4.1.3 Generation Units Data

The required units data for DP consists of:

- Max. and min. MW,
- Minimum up and down times .
- The initial conditions (hours off-line &on-line).
- Start up costs (cold & hot).
- Incremental fuel consumption rate (ton/MWh).
- No load consumption rate (Ton/hour).
- Full load consumption rate (Ton/hour).
- Fuel cost(Dinar/Ton).

4.1.4 Capacity Ordering of the Units

In DP approach :

Firstly, the unit combinations or states are generated with total number of states equal to (2^n-1) in case of complete enumeration and equal n in case of priority order, where n is the number of units in the system.

Secondly, the unit combinations or states are ordered with the sum of the maximum capacity of all units in the combination, this maximum net capacity ordering of the units combinations is used in DP approach each period to examine the states for dispatching the load.

4.1.5 Load Pattern

The loads for all sub periods of the scheduling total period are given for dispatching the generation and calculating the cost of each sub period and the total cost of the scheduling period.

4.1.6 Calculation In Forward DP Algorithm

Starting at the first hour k with the given initial state at hour 0, the least total cost of all states I, are calculated using the units data and the formula below and observing the unit constraints(min. up & down times, initial conditions, capacity limits ,,,,) and the load of the period P (MW):

$$\mathbf{Fcost(K,I) = \min_{\{L\}}[Pcost(K,I) + Scost(K-1,L:K,I) + Fcost(K-1,L)]}$$

Where {L} for the first hour is the given initial state.

. The minimum cost commitments for the first hour are saved and the infeasible states are discarded.

The forward DP is repeated for all sub periods (hours) and the minimum cost commitments are saved each sub period.

Finally the optimal unit commitment scheduling (lower cost states) are listed with the minimum cost of each sub period and the total cost of the scheduling period.

4.2 The Computer Program For Solving UCP

In solving UCP by complete enumeration the total number of combinations to try (test) each sub period is equal to $(2^n - 1)$, and for a period of m sub-period or intervals, the total number of possible combinations is $(2^n - 1)^m$, which became a very large number to test for the whole period .

For example: in systems with 5, 10 and 20 generating units and for a scheduling period one day consists of 24 sub periods (each sub period is one hour long), the total value of combinations or states to be tested will be as follows:

n	$\mathbf{(2^n - 1)^{24}}$
4	$\mathbf{6.2x10^{35}}$
8	$\mathbf{1.73x10^{72}}$
10	$\mathbf{3.12x10^{144}}$

These very large numbers of combinations indicates that the manual calculations will be very difficult to handle the UCP, so creating a computer program (software) will simplify solving this problem giving high dimensionality of possible solutions in a relatively short run-time.

So, in what follows we transfer the forward DP algorithm to a computer program using Visual BasicVB language .

4.3 Visual Basic UC-Program

The structure of the UC-program consist of five objects, four forms plus a module as follows:

-Form1 (commit.frm)

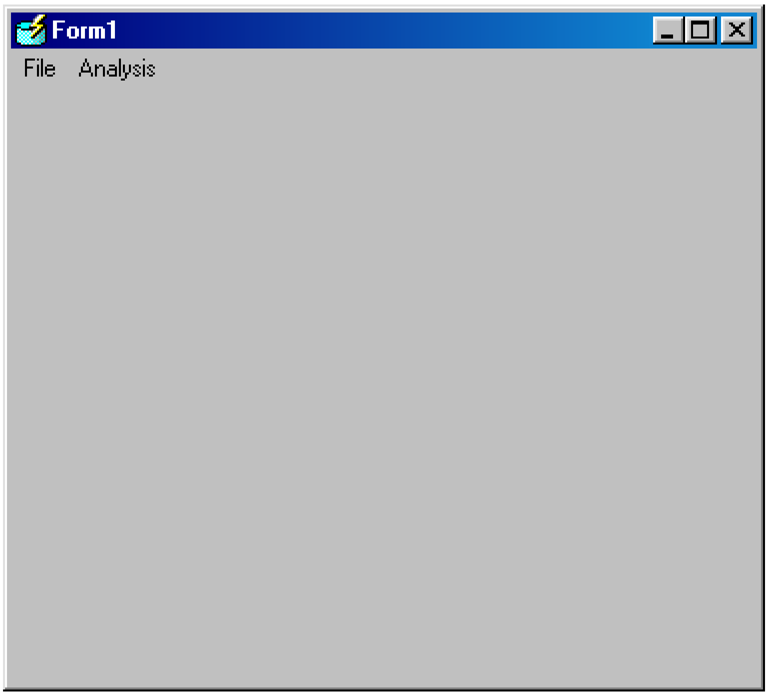
-Form2 (form2.frm)

-Form3 (form3.frm)

-Form4 (form4.frm)

-Module1 (module1.bas)

4.3.1 **Form1** (commit .frm) shown below:



Form1 contains the main program procedures and functions arranged as follows :

1-Function SetState

2-Function Sort

3-public sub BestStates

4-public sub Order

5-public sub Feas

6-public sub EDC

7-public sub Final_output

8-private sub Menucommit

9-private sub Menueditgen

10-private sub Menuexit

11-private sub Menuload

12-private sub Menuopen

13-private sub Menusave

Form1 documentation:

- **Function SetStates**

  Generate the state that contains only the units given on-line(+ve unit status) i.e initial state.

- **Function Sort**

  Sorting the states according to unit no. in the list of the units to compare the states so that the units must be sorted in ascending order i.e state 213 must appear as 123.

- **Public sub Beststates**

  Subroutine to give an order table of unit states (setP) every period in which possible states (not equal to infinity) arranged in a list according to cost, least first i.e best states (orderindex.)

- **Public sub Order**

  Procedure to generate an order list of items with least value first to be used in determining a table of best states in the beststates sub-routine.

- **Public sub Feas**

  Procedure to test transition of units (on/off), from last state to the present state, in which a check to the min-down time and the min-up time of the unit is done:

  Firstly, if the unit is down (off) in the last state we test the min-down time of the unit to see whether it can be started up this period , if the hours the unit is down is less than the min-down time of the unit it cannot be started up this period and will still be down , so the time the unit is down is increased by one period hours , and if the hours the unit down is greater than the min-down time of the unit so it can be turn on this period and the transition cost (Scost) is equal the start up cost of the unit.

  Secondly, if the unit is up (on) last period and if the hours the unit is up is less than the min-up time of the unit, the unit cannot be shut down this period so it will still be up and the time the unit is up is increased by one period hours, and if the hours the unit is up greater than the unit min-up time so the unit can be shut down and the temporary unit status will = -1 period hours.

- **Public sub EDC** (Economic Dispatch)

Procedure to perform economic dispatch of the units every period k,

Firstly we calculate the production cost of the states each period (.Pcost):

Initially we put the sum of states(i) MinMW(i)=0

MaxMW(i)=0

.Pcost(i) = 0

then we search each state , if unit j is in state i then we add the minMW(j) to the sumMinMW(i) of state i and the maxMW(j) to the sumMaxMW(i)of state i

so that : sumMin(i) = sumMin(i) + sumMin(j)

sumMax(i) = sumMax(i) + sumMax(j)

then we test the range of each state in the period to see whether the period load is within the range or not : sumMin <= .sysload <= sumMax

for state with sumMin >= .sysload or .sysload >= sumMax we put this state cost equal to infinity i.e .Pcost = 1.0E12 and this state is withdrawn.

For state where the .sysload is within the range we start dispatching the units of this state by:

Firstly, giving each unit in the state it is minMW so that

unitGen(j) = minMW(j)

Secondly, we search for the unit with minimum incremental cost in the state and load it to it is maxMW i.e giving it the difference between its maxMW and minMW,

and if there is remaining load of the period it will be distributed by loading the unit with second minimum incremental cost in the state and so on till all period load is distributed among the units of the state.

Then we calculate each unit cost by formula;

Untcost=NoLoad cost + untGen*HeatIncre*Fuel cost

And finally we calculate the state production cost which equal to the sum of the costs of all units in the state.

- **Public sub Final Output**

  Procedure to show the final optimum commitment schedule in a tabular format table, where we determine the optimum state and optimum cost of each period k, arranged in a table starting from last period to the first period and contains the following:

- final optimum cost(total cost of the schedule)
- period number.
- period optimum state number.
- unit status(ON/OFF) of the period optimum state.
- Production cost of the period optimum state in TSDD/hr. (TSDD stands for Thousand Sudanese Dinars)
- Period load(MW) .

- **Private sub Menucommit**

  Contains the main UC program execution file in which we first generate a list of all unit states (combinations of units or simply states), sorted according to the number of the unit in the units list (1,2,3,…,n) , determine the total number of states (nStates) and then redimensioning the following parameters for the DP search process:

- Table of unitStatNow: unit status for present period
- Table of unitStatLast: unit status for previous period
- SetL (nStates) list of feasible states in the last period
- SetX (nStates) list of states in the present period

- Orderindex (nStates) table returned from ordering subroutine

- Table of Fcost(nStates) cost of state at period K

- Table of Pcost(nStates) production cost table at period K

- Table of Path(nStates) optimal states in the last period

Then we call SetState function to generate the initial state (unitInitStat) given for period 0 and search the list of states for the unitInitStat number and determine it is number in the list.

InitStat = i

then we give the X and N parameters the total number of states i.e we use the complete enumeration scheme.

- Initially in period 0 we put:

.Fcost = infinity

all unit status equal to 0.

and for the given initial state we put the

.Fcost = 0

.Pcost = 0

.Path = 0

then we generate a matrix which contains the initial state of each unit (number of hours on or off) at period 0.

- In period k=1 (first period)

we put the unitStatLast of the present period equal to unitStatNow of the previous period .

- for period 1 unitStatLast is the initially given unit status.

- then for all states we put .Fcost = infinity

.Path = 0

all unitStatNow = 0

- then we build setL (the list of the feasible states in the last period)

for period 1 setL = the initial state.

- we call Beststates procedure to get the top Nmax best states in the last period for .Path calculations in EDC .

  - we call EDC the economic dispatch procedure to calculate the states production cost(.Pcost).
  - we call Beststates procedure to built the list of states in the present period SetX.

- we call the Feas procedure to search the transition from states in last period SetL, to the states in present period SetX, and check whether it is feasible or not , if it is feasible we calculate the .Path cost of these feasible paths using the formula

  Pathcost

  = .Fcost (k-1,LStates)+ Scost(k-1,LStates;k,Xstates)+.Pcost(Xstates)

  Where k is the present period

  k-1 is the last period

if the the Path cost is less than or equal to the cost of the present states Xstates

.Pathcost <= Fcost (Xstates)

then we put

.Fcost(Xstates)= Pathcost (minimum Path cost)

and

unitStatNow = unitStatTemp(the temporary status during search period)

Path(Xstates) = Lstates points to the last best states in the previous period

we repeat for all periods k.

Then we call Final output procedure to show the final optimum unit commitment schedule output .

- **Private sub menueditgen**

Call form2 to edit the generator units data as follows;

unit generator no.

unit minMW, unit maxMW, HeatIncrement

NoLoad cost, StartUp cost, Fuel cost

minUP time, minDown time, unit Initial state

- **Private sub menuexit**

The procedure to close the form.

- **Private submenuload**

To call form3 for edit load data as follows :

No of periods

period length

periods load.

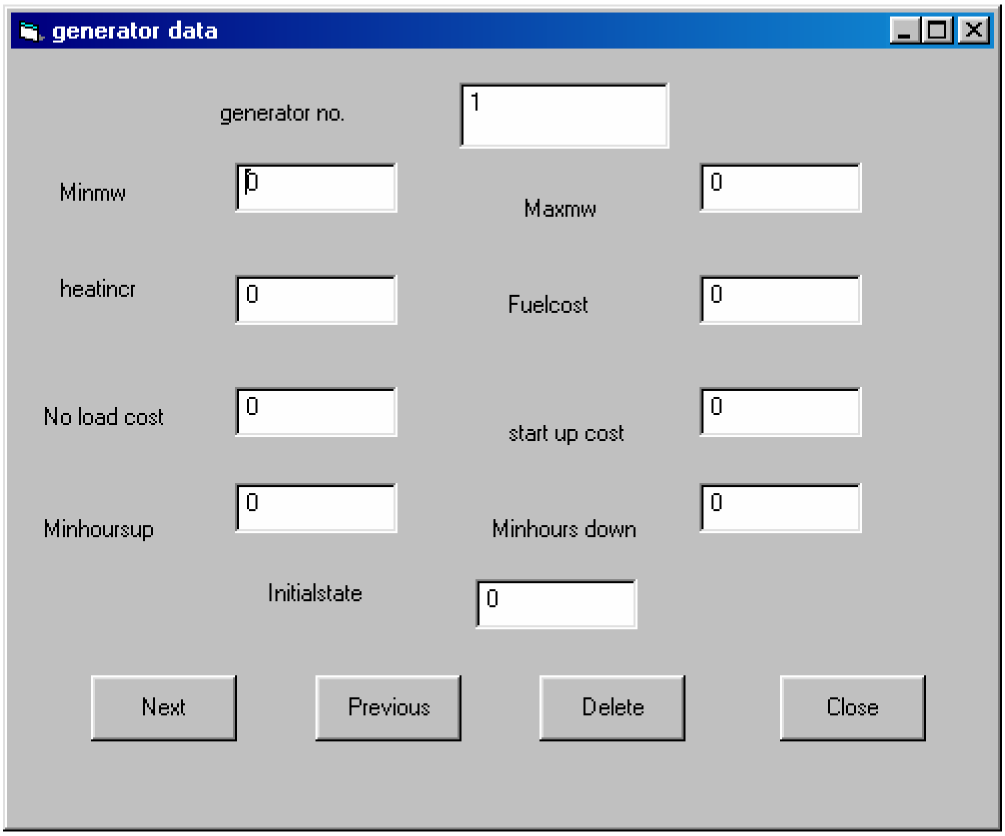
- **Private sub menuopen**

Procedure to open the data files to read for commit procedure.

-Private sub menusave

Procedure to save the data files.

4.3.2 **Form2** (form2.frm) shown below:



Contains:

1- commands to control the generator units data:

- next command go forward and show the next unit data in the list.
- previous command go backward and show the previous unit data in the list
- delete command used to delete the generator unit data and pull back one step all the units placed after the deleted unit in the list.
- hide command used to close the form.

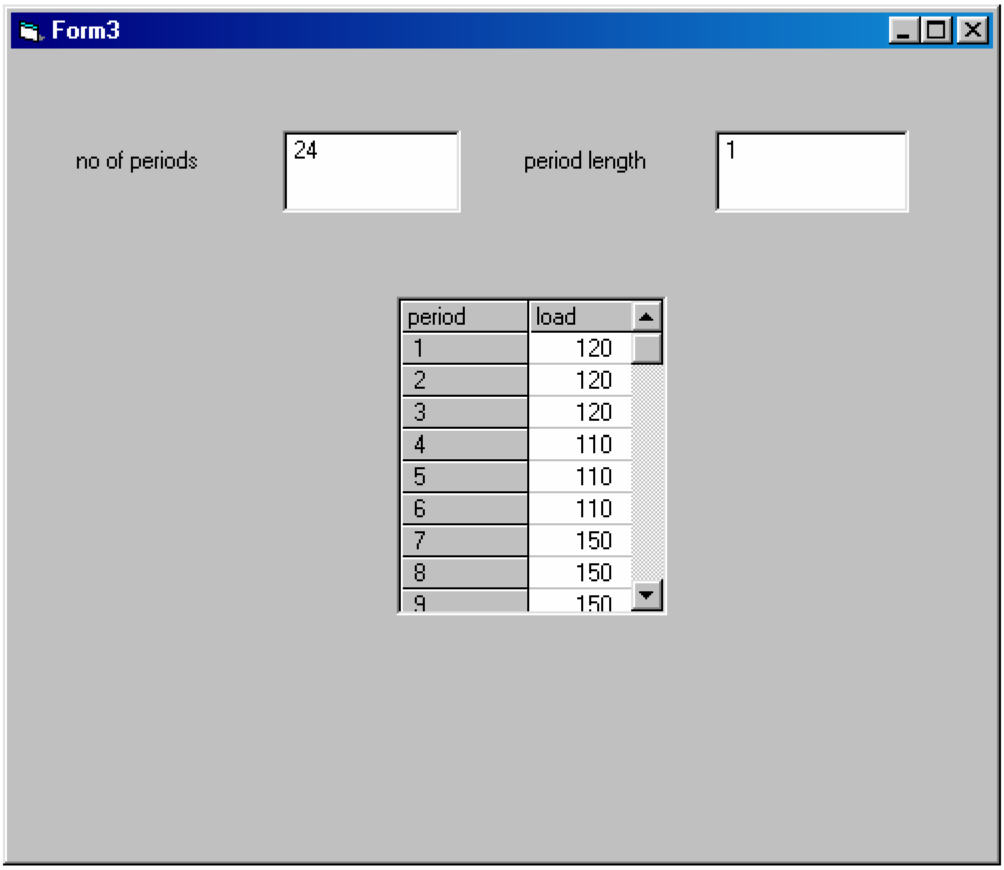
2- procedures to enter the generator units data for executing the program and arranged as follows:

- Text1 contains the value of the unit MinMW .
- Text2 contains the value of the unit MaxMW.
- Text3 contains the value of the fuel cost.
- Text4 contains the value of the unit incremental cost.
- Text5 contains the value of the unit noload cost.
- Text6 contains the value of the unit start up cost.

- Text7 contains the value of the unit minup time.
- Text8 contains the value of the unit mindown time.
- Text9 contains the value of the unit initial status.

Text10 contains the value of the unit number in the list.

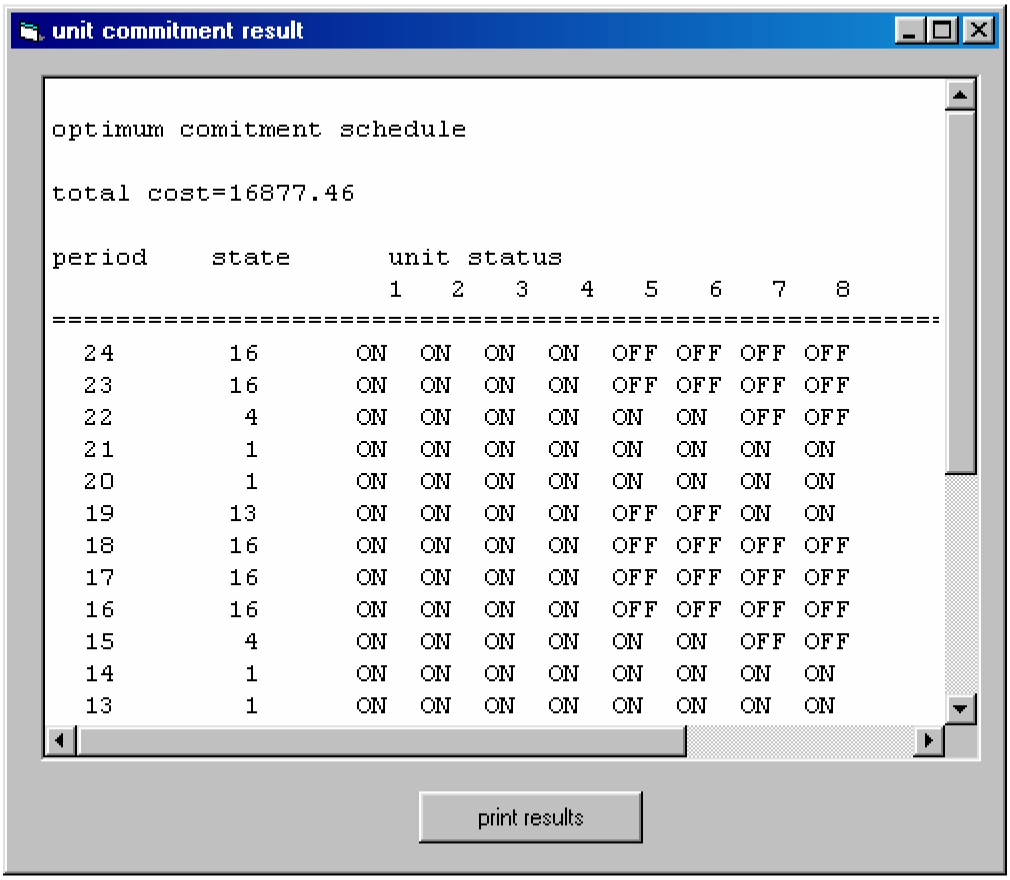
4.3.3 **Form3** (form3.frm) shown below:



contains the procedures to enter;

- number of periods
- period length
- load of each period:

4.3.4 **Form4** (form4.frm) shown below:



Contains the procedures to:

- print the result.

Show the result in the result form

4.3.5 Module1 (module1.bas)

Contains the declaration of the public variables that are available to all applications in the program.

5 UNIT COMMITMENT OF KHARTOUM NORTH POWER STATION

In order to assign an optimum unit commitment scheduling of the steam and gas thermal units of Khartoum North Power Station (KNPS) we apply the Dynamic Programming (DP) solution method to tackle the unit commitment problem of KNPS.

In the following a brief description of the contents of KNPS was given first then a description of the necessary parameters for DP solution and the data collected from KNPS were presented and lastly the application of DP computer program (Visual Basic software) to KNPS unit commitment problem and the output result was presented.

5.1 Khartoum North Power Station Structure

Khartoum North power station is located in Khartoum area and consists of four steam units fired on furnace (HFO- heavy fuel oil) and four gas turbine units fired on gas oil.

The steam units 1&2 were commissioned in 1984 and 1986 respectively and each rated at 33MW with available capacity of 30 MW , the steam units 3&4 were commissioned in 1993 and rated at 60 MW with available capacity of 50 MW for each unit. These four steam units are connected to the network through four transformers 11/110KV rated at (2x41.25 MVA and 2x75 MVA).

The gas units 1&2 were installed in 1992 and rated at 20 MW with available capacity of 17 MW for each unit, the gas units3&4 were installed in 2001 and rated at 25 MW with available capacity of 20 MW for each unit. The gas units1&2 are connected to the network in the 33KV busbar through two transformers 11/33KV (each rated at 23 MVA) and the gas units 3&4 were connected to the network 110 KV busbar through one transformer 11/110KV rated at 60 MVA.

The total installed capacity of KNPS is 276 MW while the total current available capacity is about 234 MW.

5.2 DP Parameters of KNPS

The necessary parameters for running the dynamic programming solution of the unit commitment problem comprises:

1- capacity limits of the unit (min. & max. MW output)

2- unit minimum up and down times.

3- unit start up cost

4- unit incremental fuel consumption rate

5- unit initial status

6- fuel cost

7- period & period load pattern

5.2.1 Unit Capacity Limits of KNPS

The data of min. and max. output MW of the four steam units and the gas units 1&2 was collected from the validation report prepared by EDF(France Electric Company) in 1999 while the data for the gas units 3&4 was provided by the operation engineer at the station.

The data of the eight units including the designed output power, terminal voltage, min. MW and max. MW available are tabulated below:

GENERATING UNIT	P_n	V_n	Pmin.	Pmax.
ST UNIT1	33 MW	11.8 KV	15 MW	30 MW
ST UNIT2	33 MW	11.8 KV	15 MW	30 MW
ST UNIT3	60 MW	11 KV	30 MW	50 MW
ST UNIT4	60 MW	11 KV	30 MW	50 MW
G UNIT1	18 MW	11 KV	5 MW	17 MW
G UNIT2	18 MW	11 KV	5 MW	17 MW
G UNIT3	25 MW	11 KV	5 MW	20 MW
G UNIT4	25 MW	11 KV	5 MW	20 MW

5.2.2 Unit Minimum Up & Down Times

The minimum up time constraint states that when a unit is running it must be up for at least T_{up} hours and the minimum down time states that when a unit is down it must stay down for at least T_d hours, these constraints arise from physical and economical considerations.

The data for these constraints is not available in the station documents so it was obtained from the operation data after it was adjusted by the operation engineer of the station.

The data of the min. up and down times for the units of KNPS are provided in the following table:

GENERATING UNIT	Min. up time hours	Min. down time hours
ST UNIT1	2	4
ST UNIT2	2	4
ST UNIT3	2	4
ST UNIT4	2	4
G UNIT1	0.2	0.25
G UNIT2	0.2	0.25
G UNIT3	0.2	0.25
G UNIT4	0.2	0.25

5.2.3 Start Up Cost

When starting a thermal unit the temperature and pressure move slowly. Therefore an amount of energy (fuel) must be expended to bring the unit up to full-speed (on-line),this amount of energy does not result in any MW power and known as start up cost.

The start up cost of thermal units vary from cold start when the unit is cold to a hot start when the unit is recently turned-off and still relatively close to the operating temperature.

For KNPS thermal units we use the cold start cost and we collect the data from the operation log-sheet at the station.

The start up consumption in tons of fuel of the eight units are presented in the table below:

GENERATING UNIT	Start up consumption in tons of fuel	Start up cost In SDD
ST UNIT1	6.5 HFO	294775
ST UNIT2	6.5 HFO	294775
ST UNIT3	5.4 HFO	244890
ST UNIT4	5.4 HFO	244890
G UNIT1	0.31 GAS OIL	38246
G UNIT2	0.31 GAS OIL	38246
G UNIT3	0.31 GAS OIL	38246
G UNIT4	0.31 GAS OIL	38246

5.2.4 Incremental Fuel Consumption Rates

To run the DP solution, the data of the incremental fuel consumption rate (tons/MWh) was used instead of the incremental heat rate (MBtu/MWh) because there is no available heat rate data for the KNPS units.

Firstly the fuel consumption rates in(tons/hour) at discrete output point of each unit was collected from the operation log sheet at the station as follows:

GENERATING UNIT		ST 1	ST 2	ST 3	ST 4	G 1	G 2	G 3	G 4
Fuel Consumption Rate In Tons/hour At discrete o/p Levels	0 MW	3.5	3.5	1.6	1.6	1.9	1.9	2.2	2.2
	5 MW	3.65	3.65	1.9	1.9	2.1	2.1	1.62	1.62
	6 MW	3.67	3.67						
	7 MW	3.69	3.69						
	8 MW	3.71	3.71						
	9 MW	3.75	3.75	3.32	3.32				
	10 MW	3.82	3.82			3.89	3.89	4.05	4.05
	11 MW	4	4						
	12 MW	4.3	4.3						
	13 MW	4.5	4.5						
	14 MW	4.7	4.7						
	15 MW	4.95	4.95			5.49	5.49	4.455	4.455
	16 M1	5.2	5.2			5.8	5.8		
	17 MW	5.5	5.5			6.2	6.2	7.29	7.29
	18 MW	5.8	5.8	5.38	5.38				
	19 MW	6.05	6.05						
	20 MW	6.3	6.3					7.695	7.695
	21 MW	6.65	6.65						
	22 MW	6.91	6.91						
	23 MW	7.3	7.3						
	24 MW	7.6	7.6						
	25 MW	7.95	7.95						
	26 MW	8.3	8.3						
	27 MW	8.7	8.7						
	28 MW	9.1	9.1						
	29 MW	9.7	9.7						
	30 MW	9.95	9.95	8.42	8.42				
	50 MW			12.4	12.4				

Secondly a simplified model of the unit characteristics with only single step between no-load consumption rate (ton/hour) and the full load consumption rate (ton/hour) was used.
Then we calculate the incremental fuel consumption rate by applying this formula:

The incremental fuel consumption rate in (Ton/MWh) =

$$\frac{\text{Full load fuel consumption rate(Ton/h) - no load fuel consumption rate(Ton/h)}}{\text{Full load Power (MW)}}$$

The incremental fuel consumption rate of each unit is calculated and shown below:

GENERATING UNIT	Unit Max.MW	No-load consumption rate in Ton/hour	Full- load consumption rate in Ton/hour	Incremental fuel consumption rate in (Ton/MWh)
ST UNIT1	30	3.5	9.95	.215
ST UNIT2	30	3.5	9.95	.215
ST UNIT3	50	1.6	12.4	.225
ST UNIT4	50	1.6	12.4	.225
G UNIT1	17	1.9	6.2	.253
G UNIT2	17	1.9	6.2	.253
G UNIT3	20	2.2	7.695	.274
G UNIT4	20	2.2	7.695	.274

5.2.5 Fuel Cost

The steam units of KNPS burns furnace fuel (HFO-heavy fuel oil) while the gas units burns gas oil fuel .
The furnace fuel is delivered to KNPS by road tankers and railway tankers from ElObied refinery and the gas oil fuel is delivered by pipeline from Gailli refinery.

The transportation rates and the prices of the two types of fuel used in KNPS as provided by Energy Resources Department of NEC in 2006 is shown in the tables below:

Transportation rate to KNPS in SDD/TON	
Road tankers- HFO	7650
Railway tankers-HFO	7280
Pipeline-GAS OIL	1027

Fuel type	Price of fuel in SDD/TON	Price of fuel at KNPS in SDD/TON
Furnace(HFO)	37700	45350*
Gas oil	122350	123377

* the road rates was used because it is the main transportation means to KNPS.

5.2.6 Periods and Load Pattern

A 24-hour period(one day) was used with 1-hour period length to run the unit commitment program and then load pattern of 24 constant MW each period was constructed taking into consideration the daily load curve of the dispatch center of NEC and the Max. and Min. available capacity of KNPS .

The 24- hour load pattern is shown below:

Time	Load in MW	Time	Load in MW
Hour 1	120	Hour 13	230
Hour 2	100	Hour 14	220
Hour 3	80	Hour 15	200
Hour 4	80	Hour 16	150
Hour 5	100	Hour 17	150
Hour 6	120	Hour 18	180
Hour 7	120	Hour 19	220
Hour 8	150	Hour 20	230

Hour 9	150	Hour 21	230
Hour 10	180	Hour 22	200
Hour 11	200	Hour 23	180
Hour 12	230	Hour 24	150

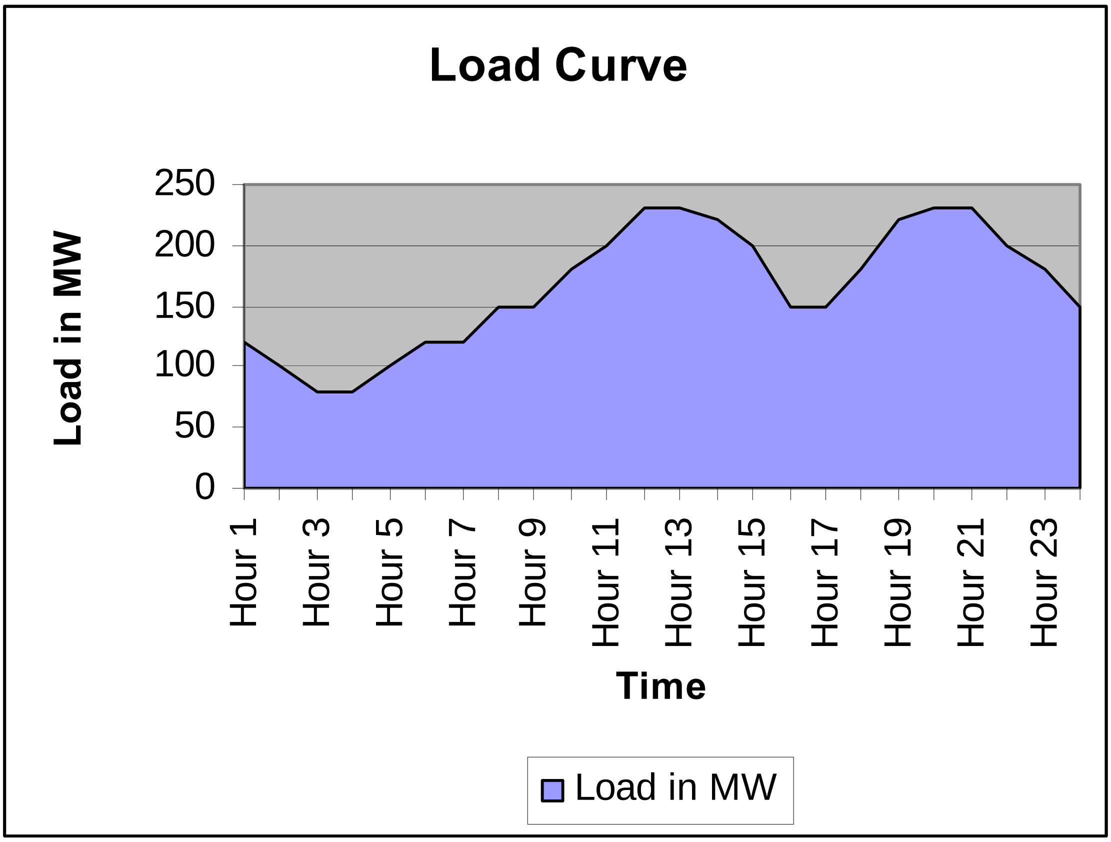


Fig. 5.1 : KNPS Daily Load Curve.

5.2.7 Units Initial Status

The schedule was started in hour1 where all the steam units are on in the previous hour 0 and all the gas unit are off in the previous hour 0 and then accordingly the units initial states was shown in the table below:

GENERATING UNIT	Unit initial condition Hour off-line(-) &Hours on-line(+)
ST UNIT1	+18

ST UNIT2	+18
ST UNIT3	+24
ST UNIT4	+24
G UNIT1	-3
G UNIT2	-3
G UNIT3	-4
G UNIT4	-4

5.3 Application of the Unit Commitment Program to KNPS

First the generator units data collected from KNPS as shown in the table below was entered in form2 of the program and then the load data (no. of periods, periods load and the period length) was entered in form3 of the program and these data was saved in drive C with name KNPS.DAT.

Unit	Min MW	Max. MW	Incremental consumption Rate in Ton/MWH	No load cost rate in TSDD/H*	Start up cost in TSDD	Fuel cost in TSDD /TON	Min Up time hours	Min down time hours	Unit initial status
ST1	15	30	0.215	158	279	45	2	4	+18
ST2	15	30	0.215	158	279	45	2	4	+18
ST3	30	50	0.225	72	243	45	2	4	+24
ST4	30	50	0.225	72	243	45	2	4	+24
G1	5	17	0.253	234	38	123	0.2	0.25	-3
G2	5	17	0.253	234	38	123	0.2	0.25	-3
G3	5	20	0.274	271	38	123	0.2	0.25	-4
G4	5	20	0.274	271	38	123	0.2	0.25	-4

- TSDD (thousand Sudanese Dinars).

Then the program was run from form1 by opening the data file C:\ KNPS.DAT. and then the main execution procedure analysis "unit commitment" in form1 is triggered and the final optimum unit commitment scheduling result was obtained as shown below.

5.4 Result

The result include the 24 periods listed from the last period down to first period.

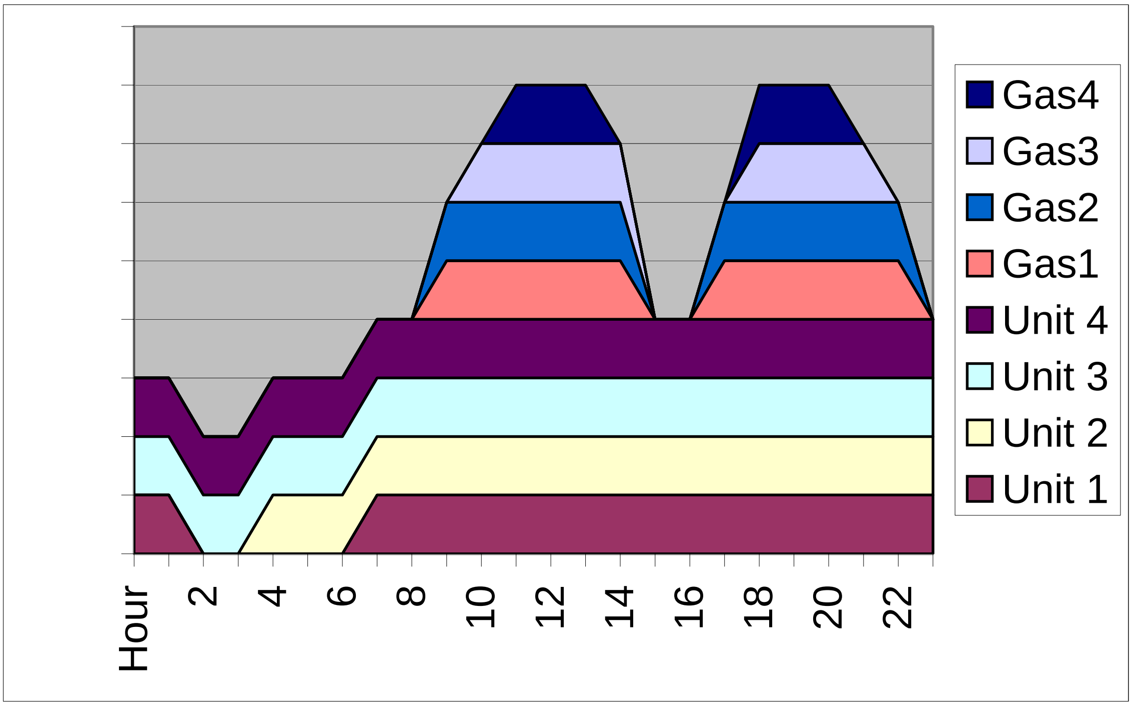
In each period row the number of the best state, unit status (ON/OFF), period production cost in (TSDD/hr) and period load (MW) were shown. Finally the total optimum cost is displayed in the top of the table below .

Optimum Commitment Schedule

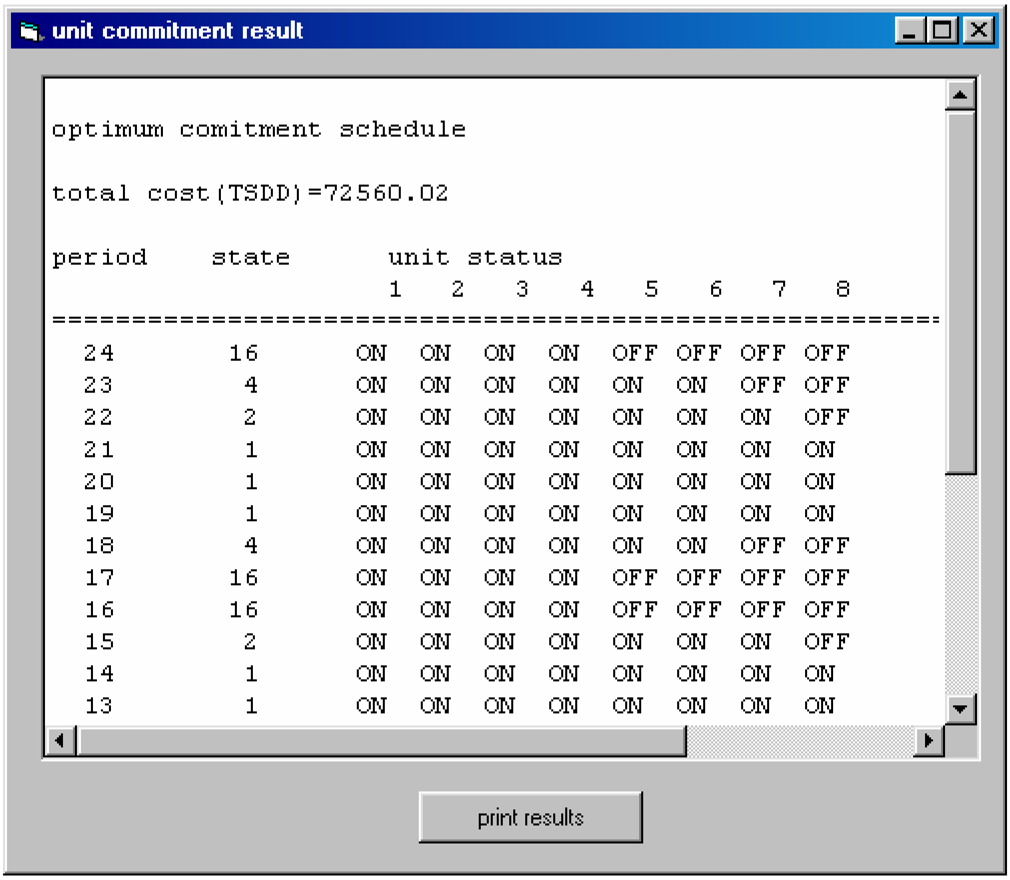
Total cost (TSDD)=72560.02

period	state	unit status									
		1	2	3	4	5	6	7	8	TSDD/hr	MW
24	16	ON	ON	ON	ON	OFF	OFF	OFF	OFF	1952	150.000
23	4	ON	ON	ON	ON	ON	ON	OFF	OFF	3143	180.000
22	2	ON	ON	ON	ON	ON	ON	ON	OFF	4052	200.000

21	1	ON	ON	ON	ON	ON	ON	ON	ON	5334	230.000
20	1	ON	ON	ON	ON	ON	ON	ON	ON	5334	230.000
19	1	ON	ON	ON	ON	ON	ON	ON	ON	4997	220.000
18	4	ON	ON	ON	ON	ON	ON	OFF	OFF	3143	180.000
17	16	ON	ON	ON	ON	OFF	OFF	OFF	OFF	1952	150.000
16	16	ON	ON	ON	ON	OFF	OFF	OFF	OFF	1952	150.000
15	2	ON	ON	ON	ON	ON	ON	ON	OFF	4052	200.000
14	1	ON	ON	ON	ON	ON	ON	ON	ON	4997	220.000
13	1	ON	ON	ON	ON	ON	ON	ON	ON	5334	230.000
12	1	ON	ON	ON	ON	ON	ON	ON	ON	5334	230.000
11	2	ON	ON	ON	ON	ON	ON	ON	OFF	4052	200.000
10	4	ON	ON	ON	ON	ON	ON	OFF	OFF	3143	180.000
9	16	ON	ON	ON	ON	OFF	OFF	OFF	OFF	1952	150.000
8	16	ON	ON	ON	ON	OFF	OFF	OFF	OFF	1952	150.000
7	144	OFF	ON	ON	ON	OFF	OFF	OFF	OFF	1504	120.000
6	144	OFF	ON	ON	ON	OFF	OFF	OFF	OFF	1504	120.000
5	144	OFF	ON	ON	ON	OFF	OFF	OFF	OFF	1301	100.000
4	208	OFF	OFF	ON	ON	OFF	OFF	OFF	OFF	954	80.000
3	208	OFF	OFF	ON	ON	OFF	OFF	OFF	OFF	954	80.000
2	80	ON	OFF	ON	ON	OFF	OFF	OFF	OFF	1301	100.000
1	80	ON	OFF	ON	ON	OFF	OFF	OFF	OFF	1504	120.000



Graphical Representation of the result (24 hours).


unit commitment result

optimum comitment schedule

total cost(TSDD)=72560.02

period	state	unit status 1	2	3	4	5	6	7	8
24	16	ON	ON	ON	ON	OFF	OFF	OFF	OFF
23	4	ON	ON	ON	ON	ON	ON	OFF	OFF
22	2	ON	ON	ON	ON	ON	ON	ON	OFF
21	1	ON	ON	ON	ON	ON	ON	ON	ON
20	1	ON	ON	ON	ON	ON	ON	ON	ON
19	1	ON	ON	ON	ON	ON	ON	ON	ON
18	4	ON	ON	ON	ON	ON	ON	OFF	OFF
17	16	ON	ON	ON	ON	OFF	OFF	OFF	OFF
16	16	ON	ON	ON	ON	OFF	OFF	OFF	OFF
15	2	ON	ON	ON	ON	ON	ON	ON	OFF
14	1	ON	ON	ON	ON	ON	ON	ON	ON
13	1	ON	ON	ON	ON	ON	ON	ON	ON

print results

Result Form

6 CONCLUSIONS

The result gives a real optimal unit commitment schedule for the steam and gas units of Khartoum North Power Station (KNPS) which are obtained from repeating the forward dynamic programming (DP) algorithm program for 24 hour period and using the complete enumeration scheme, taking into consideration the units capacity limits, minimum up and down times, start up costs and observing the load pattern specified for the 24 hour period.

Recognizing that initially the 4 steam units were given on line unit2 was turned off in hour 1:00 (the first hour of the period) and in hour 3:00 when the load decreased unit1 also turned off and in hour 5:00 unit2 is again started instead of unit1 because of unit down time restriction.

In hour 10:00 when the load exceed the maximum MW capacity of the 4 steam units (160MW) the program firstly start up both gas units1&2 and then start up gas units3&4 in hours 11:00 &12:00 respectively.

The commitment schedule shows that the steam units3&4 are on-line for all the 24 hour period of the schedule that because of their higher max. capacity (50MW each) and their low incremental fuel cost in comparison to the incremental fuel cost of the gas units. This is because the steam units burns furnace (HFO) with price almost one third the price of gas oil fuel that gas units burns, this explains why gas units are commited only for peak loads even though they have almost negligible up and down times restrictions.

The results also shows that for power systems with different type of power plants the unit commitment scheduling is effective in determining the units that are committed on-line every period and also which type of power plant are used.

Finally the computer program developed from the forward dynamic programming algorithm to solve unit commitment problem is very effective and gives accurate results in a short run time although the high dimensionality of the problem with 255 possible states to search every hour.

Further work in the context of the unit commitment problem needs to account for the whole network, including the hydro units. For the hydro units the objective function is to optimize the hydro resources, through either flow control or reservoir target level control as constraints. The overall objective, of course, is to minimize the production costs of the thermal units while at the same time meeting the hydro generation constraints. This is recommended as further work based on the same modules presented in this program and adding the necessary inputs for the hydro generation. The hydro constraints are to be inserted into the program function, together with other hydrological data such as inflow forecast for the next 24 hours, irrigation requirements.. etc.

References

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3- **William Dhaeseleer,**Long Term Unit Commitment Optimization for Large Power Systems,**University of Leuven,Belgium.**

4- **B.H.Chowdhury,University of Wyoming & Salfur Rahman,Virginia Tech.,**A Review of Recent Advances in Economic Dispatch, **IEEE Nov1990.**

5- **Raymond.B Jonson,Shmuel S,Oren, and Alva J.Svoboda,** Equity and Efficiency of Unit Commitment in Competitive Electricity Market,**University of Calfornia 1996**

6- **NEC ,**Data Validation Report, **by EDF , 1999**

7- **NEC,** Generation Data Book, **by PB Power, Oct 2006.**

8- **NEC,** Transmission Planning Report, **by PB Power, Nov 2006.**

9- **Fadi A/Elkarim ,** Visual Basic 6, **Ray Publishing& Science, 2002**

Appendix

Contains the

Visual Basic Program codes

FORM1

```
Function SetState(unitstates() As Integer, n As Integer) As String
Dim i As Integer
SetState = ""
For i = 1 To n
   If unitstates(i) > 0 Then
      SetState = SetState + Trim(str(i))
   End If
Next i
End Function

 Function Sort(st As String) As String
Dim temp As String
Sort = ""
temp = Mid(st, 1, 1)
Do While st <> ""
   For k = 2 To Len(st)
   If Val(Mid(st, k, 1)) < Val(temp) Then
   temp = Mid(st, k, 1)
   End If
   Next k
   Sort = Sort + temp
   st = Left(st, InStr(st, temp) - 1) + Mid(st, InStr(st, temp) + 1)
   temp = Mid(st, 1, 1)
Loop

End Function

Public Sub BestStates(setP() As Integer, cost() As Single, Lim As Integer, Max As
Integer)
Dim done As Boolean, index As Integer
nStates = UBound(setP, 1)
Call Order(cost, nStates)
done = False
Lim = 0
Do While Not done And (Lim < Max)
   index = orderindex(Lim + 1)
   If cost(index) = 1000000000000# Then
      done = True
   Else
      Lim = Lim + 1
      setP(Lim) = index
   End If
Loop
End Sub

Public Sub Order(orderTable() As Single, numOrder As Integer)
Dim Stopp As Boolean
Dim top As Integer, last As Integer, indx As Integer
```

```
Dim nxt() As Integer
ReDim nxt(nStates)
For i = 1 To numOrder
   If i <= 1 Then
      top = 1
      nxt(1) = 0
   Else
      j = top
      last = 0
      Do
         Stopp = True
         If orderTable(i) > orderTable(j) Then
            last = j
            j = nxt(j)
            Stopp = (j = 0)
            If Stopp Then
               nxt(last) = i
               nxt(i) = 0
            End If
         Else
            If j <> top Then
               nxt(last) = i
               nxt(i) = j
            Else
               top = i
               nxt(i) = j
            End If
         End If
      Loop Until Stopp
   End If
Next i
indx = 1
j = top
Do
   orderindex(indx) = j
   j = nxt(j)
   indx = indx + 1
Loop Until j = 0
End Sub

Public Sub Feas()
Valid = 1
Scost = 0
j = 1
Do While Valid = 1 And j <= Nunits
   If unitStatLast(lState, j) < 0 Then
      If InStr(unitState(xState), Trim(str(j))) <> 0 Then
         If (-unitStatLast(lState, j) * Length) < minDown(j) Then
            Valid = 0
         Else
```

```
            unitStatTemp(j) = 1
            Scost = Scost + StartUp(j)
         End If
      Else
         unitStatTemp(j) = unitStatLast(lState, j) - 1
      End If
   Else
      If InStr(unitState(xState), Trim(str(j))) <> 0 Then
         unitStatTemp(j) = unitStatLast(lState, j) + 1
      Else
         If (unitStatLast(lState, j) * Length) < minUp(j) Then
            Valid = 0
         Else
            unitStatTemp(j) = -1
         End If
      End If
   End If
   j = j + 1
Loop

End Sub

Public Sub EDC()
Dim Minunt As Integer, Stopp As Boolean, sumMax As Single, sumMin As Single
Dim minInc As Single, untCost As Single, dispLoad As Single, untRange As Single
With Period_Data(k)
For i = 1 To nStates
   sumMin = 0
   sumMax = 0
   .Pcost(i) = 0
   For j = 1 To Nunits
      If InStr(unitState(i), Trim(str(j))) <> 0 Then
         sumMin = sumMin + MinMW(j)
         sumMax = sumMax + MaxMW(j)
      End If
   Next j
   If sumMin >= .sysLoad Or .sysLoad >= sumMax Then
      .Pcost(i) = 1000000000000#
   Else
      dispLoad = .sysLoad - sumMin
      For j = 1 To Nunits
         If InStr(unitState(i), Trim(str(j))) <> 0 Then
            unitGen(j) = MinMW(j)
         End If
      Next j
      Do
         minInc = 1000000000000#
         Minunt = 0
         For j = 1 To Nunits
```

```
            If InStr(unitState(i), Trim(str(j))) <> 0 And unitGen(j) = MinMW(j) And
HeatIncr(j) < minInc Then
                minInc = HeatIncr(j)
                Minunt = j
            End If
        Next j
        untRange = MaxMW(Minunt) - MinMW(Minunt)
        Stopp = dispLoad < untRange
        If Not Stopp Then
            unitGen(Minunt) = MaxMW(Minunt)
            dispLoad = dispLoad - untRange
        End If
    Loop Until Stopp
    unitGen(Minunt) = MinMW(Minunt) + dispLoad
    For j = 1 To Nunits
        If InStr(unitState(i), Trim(str(j))) <> 0 Then
            untCost = NoLoad(j) + Fuel(j) * unitGen(j) * HeatIncr(j)
            untCost = untCost * Length
            .Pcost(i) = .Pcost(i) + untCost
        End If
    Next j
  End If
Next i
End With


End Sub

Public Sub Final_Output()
Open "result.txt" For Output As #1
OptCost = 1000000000000#
opState = 0
With Period_Data(periods)
For i = 1 To nStates
  If .Fcost(i) <= OptCost Then
    OptCost = .Fcost(i)
    opState = i
  End If
Next i
'MsgBox OptCost
'MsgBox unitState(opState)
End With
Print #1, "optimum comitment schedule"
Print #1,
Print #1, "total cost(TSDD)="; Format(OptCost, "#0.00")
Print #1,
Print #1, "period    state      unit status"
  Print #1, Space(18);
For j = 1 To Nunits
Print #1, Format(str(j), "@@@@");
```

```
Next j
Print #1, "        $/hr         MW"
For j = 1 To Nunits
Print #1, "====";
Next j
Print #1, "============================================"
For k = periods To 1 Step -1
   With Period_Data(k)
   Print #1, Format(str(k), "@@@@"); "      "; Format(str(opState), "@@@"); "      ";
   For j = 1 To Nunits
      If InStr(unitState(opState), Trim(str(j))) <> 0 Then
         Print #1, "ON  ";
      Else
         Print #1, "OFF ";
      End If
   Next j
   Print #1, "   ";
   Print #1, Format(Format(.Pcost(opState), "#0"), "@@@@@@@"); "    ";
   Print #1, Format(Format(.sysLoad, "#0.000"), "@@@@@@@@@")
   opState = .Path(opState)
   End With
Next k
Close #1
End Sub

Private Sub Form_Load()

End Sub

Private Sub Menucommit_Click()

state = ""
For i = 1 To Nunits
state = state + Trim(str(i))
Next i
j = Nunits
i = 0
Do While state <> ""
   i = i + 1
   ReDim Preserve unitState(i)
   state = Sort(state)
   unitState(i) = state
  ' MsgBox unitState(i)
   borrow = True
   j = Nunits
   Do While borrow
      If InStr(state, Trim(str(j))) <> 0 Then
      state = Left(state, InStr(state, Trim(str(j))) - 1) + Mid(state, InStr(state,
Trim(str(j))) + 1)
      borrow = False
```

```
        Else
        state = state + Trim(str(j))
        j = j - 1
        End If
    Loop
Loop
nStates = i
ReDim unitStatNow(nStates, Nunits)
ReDim unitStatLast(nStates, Nunits)
ReDim setL(nStates)
ReDim setX(nStates)
ReDim orderindex(nStates)
For i = 0 To periods
    ReDim Period_Data(i).Pcost(nStates)
    ReDim Period_Data(i).Fcost(nStates)
    ReDim Period_Data(i).Path(nStates)
Next i

'MsgBox nStates
state = SetState(unitInitStat, Nunits)
For i = 1 To nStates
    If state = unitState(i) Then
        Exit For
    End If
Next i
'MsgBox i
'MsgBox unitState(i)
InitState = i
nMax = nStates
xMax = nStates
With Period_Data(0)
    For i = 1 To nStates
        .Fcost(i) = 1000000000000#
        For j = 1 To Nunits
            unitStatNow(i, j) = 0
        Next j
    Next i
    .Fcost(InitState) = 0
    .Pcost(InitState) = 0
    .Path(InitState) = 0
    For i = 1 To Nunits
        unitStatNow(InitState, i) = unitInitStat(i)
    Next i
End With
continue = True
k = 1
Do While (k <= periods And continue)
    With Period_Data(k)
    For i = 1 To nStates
        For j = 1 To Nunits
```

```
            unitStatLast(i, j) = unitStatNow(i, j)
        Next j
    Next i
    For i = 1 To nStates
        .Fcost(i) = 1000000000000#
        .Path(i) = 0
        For j = 1 To Nunits
            unitStatNow(i, j) = 0
        Next j
    Next i
    If k = 1 Then
        nLim = 1
        setL(1) = InitState
    Else
        Call BestStates(setL, Period_Data(k - 1).Fcost, nLim, nMax)
    End If
    Call EDC
    Call BestStates(setX, .Pcost, xLim, xMax)
    continue = False
    For x = 1 To xLim
        xState = setX(x)
        For n = 1 To nLim
            lState = setL(n)
            Call Feas
            If Valid = 1 Then
                PathCost = Period_Data(k - 1).Fcost(lState) + Scost + .Pcost(xState)
                If PathCost <= .Fcost(xState) Then
                    .Fcost(xState) = PathCost
                    For i = 1 To Nunits
                        unitStatNow(xState, i) = unitStatTemp(i)
                    Next i
                    .Path(xState) = lState
                    continue = True
                End If
            End If
        Next n
    Next x
    k = k + 1
    End With
Loop
If continue Then
    Call Final_Output
    Form4.Show
    Form4.Refresh
Else
    MsgBox ("there is no solution")
End If
End Sub
```

```
Private Sub menueditgen_Click()
Form2.Show
End Sub

Private Sub Menuexit_Click()
End
End Sub

Private Sub menuload_Click()
Form3.Show
End Sub

Private Sub Menuopen_Click()
cd1.DialogTitle = "open data file"
cd1.Filter = "data files (*.dat)|*.dat"
cd1.ShowOpen
filename = cd1.filename
If cd1.filename <> "" Then
Open cd1.filename For Input As #1
Line Input #1, readStr
Line Input #1, readStr
Line Input #1, readStr
Nunits = Val(readStr)
ReDim MinMW(Nunits), MaxMW(Nunits), HeatIncr(Nunits)
ReDim NoLoad(Nunits), StartUp(Nunits), Fuel(Nunits)
ReDim minUp(Nunits), minDown(Nunits), unitInitStat(Nunits)
ReDim unitStatTemp(Nunits), unitGen(Nunits)
For i = 1 To Nunits
   Line Input #1, readStr
   Line Input #1, readStr
   start = 1
      endd = InStr(readStr, " ")
      If endd = 0 Then endd = Len(readStr) + 1
      MinMW(i) = Val(Mid(readStr, start, endd - start))
      readStr = Mid(readStr, endd + 2)
      endd = InStr(readStr, " ")
      If endd = 0 Then endd = Len(readStr) + 1
      MaxMW(i) = Val(Mid(readStr, start, endd - start))
      readStr = Mid(readStr, endd + 2)
      endd = InStr(readStr, " ")
      If endd = 0 Then endd = Len(readStr) + 1
      HeatIncr(i) = Val(Mid(readStr, start, endd - start))

   Line Input #1, readStr
   start = 1
      endd = InStr(readStr, " ")
      If endd = 0 Then endd = Len(readStr) + 1
      NoLoad(i) = Val(Mid(readStr, start, endd - start))
      readStr = Mid(readStr, endd + 2)
      endd = InStr(readStr, " ")
```

```
        If endd = 0 Then endd = Len(readStr) + 1
        StartUp(i) = Val(Mid(readStr, start, endd - start))
        readStr = Mid(readStr, endd + 2)
        endd = InStr(readStr, " ")
        If endd = 0 Then endd = Len(readStr) + 1
        Fuel(i) = Val(Mid(readStr, start, endd - start))

    Line Input #1, readStr
    start = 1
        endd = InStr(readStr, " ")
        If endd = 0 Then endd = Len(readStr) + 1
        minUp(i) = Val(Mid(readStr, start, endd - start))
        readStr = Mid(readStr, endd + 2)
        endd = InStr(readStr, " ")
        If endd = 0 Then endd = Len(readStr) + 1
        minDown(i) = Val(Mid(readStr, start, endd - start))
        readStr = Mid(readStr, endd + 2)
        endd = InStr(readStr, " ")
        If endd = 0 Then endd = Len(readStr) + 1
        unitInitStat(i) = Val(Mid(readStr, start, endd - start))
Next i
Line Input #1, readStr
    start = 1
        endd = InStr(readStr, " ")
        If endd = 0 Then endd = Len(readStr) + 1
        periods = Val(Mid(readStr, start, endd - start))
        readStr = Mid(readStr, endd + 2)
        endd = InStr(readStr, " ")
        If endd = 0 Then endd = Len(readStr) + 1
        Length = Val(Mid(readStr, start, endd - start))
ReDim Period_Data(periods)
Line Input #1, readStr
start = 1
  For i = 1 To periods
        endd = InStr(readStr, " ")
        If endd = 0 Then endd = Len(readStr) + 1
        Period_Data(i).sysLoad = Val(Mid(readStr, start, endd - start))
        readStr = Mid(readStr, endd + 2)
  Next i
End If
Close #1

End Sub

Private Sub Menusave_Click()
cd1.DialogTitle = "save data file"
cd1.Filter = "data files (*.dat)|*.dat"
cd1.ShowSave
filename = cd1.filename
Open cd1.filename For Output As 1#
```

```
Print #1, "unit commitment data file"
Print #1, "-------------------------"
Print #1, Format(Nunits, "0")
For i = 1 To Nunits
Print #1, "unit " + str(i) + " data "
Print #1, Format(MinMW(i), "#0.0"); "  "; Format(MaxMW(i), "#0.0"); "  ";
Format(HeatIncr(i), "#0.000")
Print #1, Format(NoLoad(i), "#0.0"); "  "; Format(StartUp(i), "#0.0"); "  ";
Format(Fuel(i), "#0.0")
Print #1, Format(minUp(i), "#0"); "  "; Format(minDown(i), "#0"); "  ";
Format(unitInitStat(i), "#0")
Next i
Print #1, Format(periods, "#0"); "  "; Format(Length, "#0.0")
For i = 1 To periods
Print #1, Format(Period_Data(i).sysLoad, "#0.0"); "  ";
Next i
End Sub
```

FORM2

```
Private Sub Form_Activate()
   Dim response As Integer
   If Nunits = 0 Then
      response = MsgBox("no generators-add new generator?", vbYesNo)
      If response = vbYes Then
         ReDim MinMW(1), MaxMW(1), HeatIncr(1)
         ReDim NoLoad(1), StartUp(1), Fuel(1)
         ReDim minUp(1), minDown(1), unitInitStat(1)
         ReDim unitStatTemp(1), unitGen(1)
         Nunits = 1
         i = 1
         Text10.Text = i
      Else
         Form2.Hide
      End If
   Else
      i = 1
      Text10.Text = 1
   End If
End Sub

Private Sub Text1_Change()
MinMW(Val(Text10.Text)) = Val(Text1.Text)
End Sub

Private Sub Text10_Change()
Text1.Text = MinMW(Val(Text10.Text))
Text2.Text = MaxMW(Val(Text10.Text))
Text3.Text = Fuel(Val(Text10.Text))
Text4.Text = HeatIncr(Val(Text10.Text))
Text5.Text = NoLoad(Val(Text10.Text))
Text6.Text = StartUp(Val(Text10.Text))
Text7.Text = minUp(Val(Text10.Text))
Text8.Text = minDown(Val(Text10.Text))
Text9.Text = unitInitStat(Val(Text10.Text))
End Sub

Private Sub Text2_Change()
MaxMW(Val(Text10.Text)) = Val(Text2.Text)
End Sub

Private Sub Text3_Change()
Fuel(Val(Text10.Text)) = Val(Text3.Text)
End Sub

Private Sub Text4_Change()
HeatIncr(Val(Text10.Text)) = Val(Text4.Text)
End Sub
```

```
Private Sub Text5_Change()
NoLoad(Val(Text10.Text)) = Val(Text5.Text)
End Sub

Private Sub Text6_Change()
StartUp(Val(Text10.Text)) = Val(Text6.Text)
End Sub

Private Sub Text7_Change()
minUp(Val(Text10.Text)) = Val(Text7.Text)
End Sub

Private Sub Text8_Change()
minDown(Val(Text10.Text)) = Val(Text8.Text)
End Sub

Private Sub Text9_Change()
unitInitStat(Val(Text10.Text)) = Val(Text9.Text)
End S
```

FORM3

```
Private Sub Form_Activate()
Text1.Text = periods
Text2.Text = Length
Grid1.Rows = periods + 1
Grid1.Row = 0
Grid1.Col = 0
Grid1.Text = "period"
Grid1.Col = 1
Grid1.Text = "load"
For i = 1 To periods
Grid1.Row = i
Grid1.Col = 0
Grid1.Text = str(i)
Grid1.Col = 1
Grid1.CellAlignment = flexAlignCenterCenter
Grid1.Text = Period_Data(i).sysLoad
Next i
End Sub

Private Sub Form_Click()
Text3.Visible = False
End Sub

Private Sub Grid1_Click()
Text3.top = Grid1.top + Grid1.CellTop
Text3.Left = Grid1.Left + Grid1.CellLeft
Text3.Visible = True
Text3.Text = ""
Text3.SetFocus
End Sub

Private Sub Text1_Change()
periods = Val(Text1.Text)
Grid1.Rows = periods + 1
ReDim Preserve Period_Data(periods)
For i = 1 To periods
Grid1.Row = i
Grid1.Col = 0
Grid1.Text = str(i)
Next i
End Sub

Private Sub Text2_Change()
Length = Val(Text2.Text)
End Sub
```

```
Private Sub Text3_Change()
i = Grid1.Row
Grid1.CellAlignment = flexAlignCenterCenter
Grid1.Text = Text3.Text
Period_Data(i).sysLoad = Val(Text3.Text)
End Sub

Private Sub Text3_LostFocus()
Text3.Visible = False
End Sub
```

FORM4

```
Cd2.CancelError = True
On Error GoTo printerror
Cd2.Flags = cdlPDNoPageNums
Cd2.ShowPrinter
Printer.Print Text1.Text
Printer.EndDoc
Exit Sub
printerror:
MsgBox Err.Description
End Sub

Private Sub Form_Activate()
Dim txtline As String, str As String
Open "result.txt" For Input As #1
Do While Not EOF(1)
   Line Input #1, str
   txtline = txtline + Chr(13) + Chr(10) + str
Loop
Text1.Text = txtline
Close #1
End Sub

Private Sub Text1_Change()

End Sub
```

MODULE

```
Type Period_Rec
    sysLoad As Single
    Pcost() As Single
    Fcost() As Single
    Path() As Single
End Type

Global readStr As String, Nunits As Integer, MinMW() As Single, MaxMW() As
Single, HeatIncr() As Single
Global NoLoad() As Single, StartUp() As Single, Fuel() As Single
Global minUp() As Single, minDown() As Single, unitInitStat() As Integer
Global num As Integer, start As Integer, endd As Integer
Global periods As Integer, Length As Single
Global state As String, unitState() As String, nStates As Integer
Global Period_Data() As Period_Rec, setL() As Integer, nLim As Integer
Global setX() As Integer, xLim As Integer, xState As Integer, lState As Integer
Global i As Integer, j As Integer, k As Integer, m As Integer, n As Integer, x As
Integer
Global unitStatNow() As Integer, unitStatLast() As Integer
Global InitState As Integer, continue As Boolean
Global orderindex() As Integer, nMax As Integer, xMax As Integer
Global Valid As Integer, Scost As Single, unitStatTemp() As Integer
Global unitGen() As Single, PathCost As Single, OptCost As Single, opState As
Integer
Global filename As String
```